
Beauty and Charm Production

at the Fermilab Tevatron

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Fermi National Accelerator lab

b quark discovered - 1977

FERMI NATIONAL ACCELERATOR LABORATORY NEWS RELEASE

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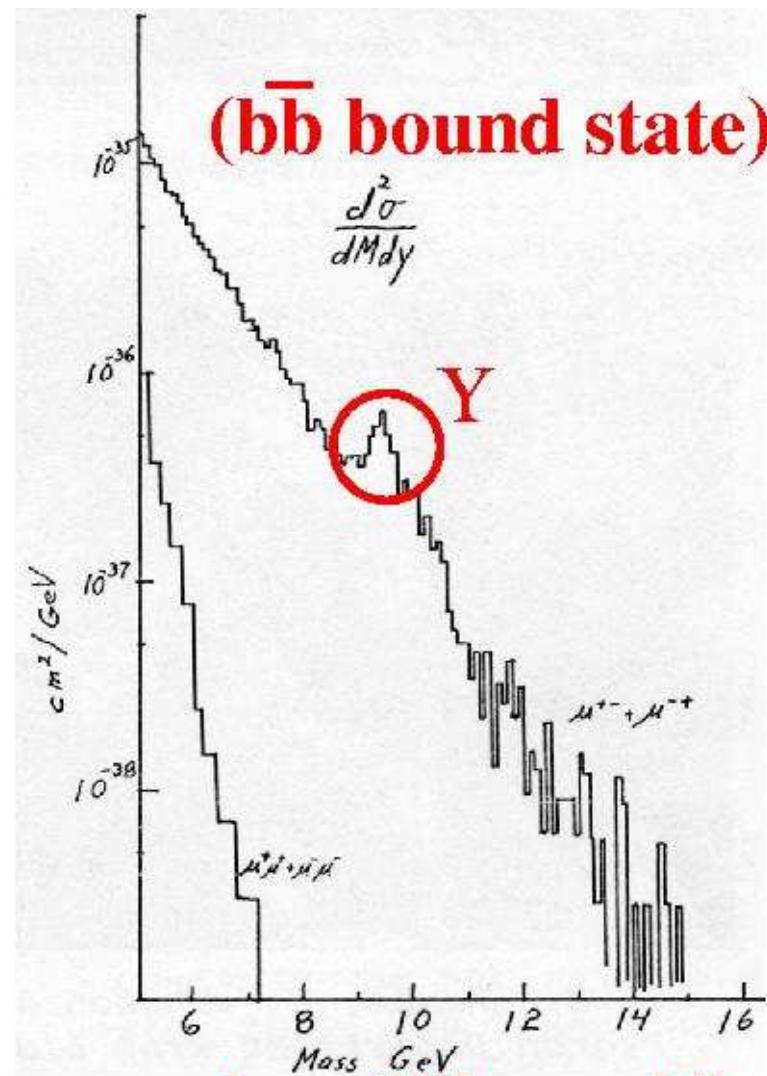
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An experimental group at the Fermi National Accelerator Laboratory announced recently that it has discovered a new particle. The new particle has a mass of 9.5 GeV. It is 10 times heavier than the proton and is the heaviest sub-nuclear particle ever seen. The new particle -- which the group has named "Upsilon" -- is interpreted by theorists to be the first hint of a whole new family of sub-nuclear particles.

The speculation that all matter is made up of small point-like objects called "quarks" has been hotly pursued in research centers all over the world in the past few years. The original theories suggested the existence of three different kinds of quarks. The "Jpsi" particles discovered at the Brookhaven National Laboratory and the Stanford Linear Accelerator Center in 1974 were the first of several discoveries which showed strong evidence of the existence of a fourth kind of quark, the "charmed" quark. It now appears as a result of the work at Fermilab that there may be a fifth quark still another constituent in the fundamental structures of matter.

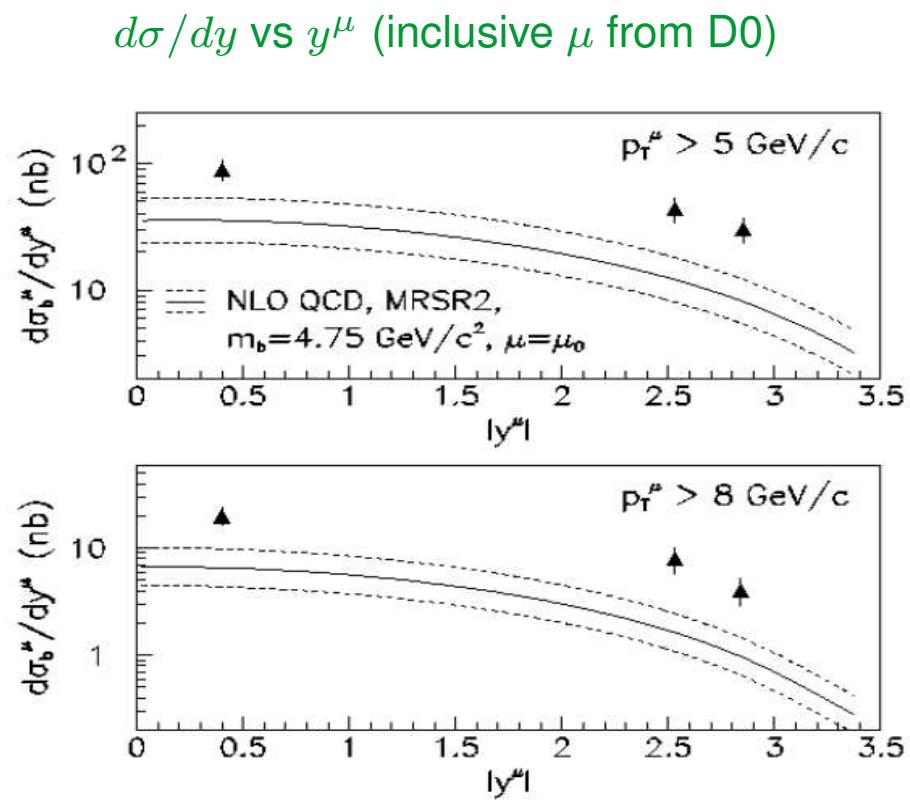
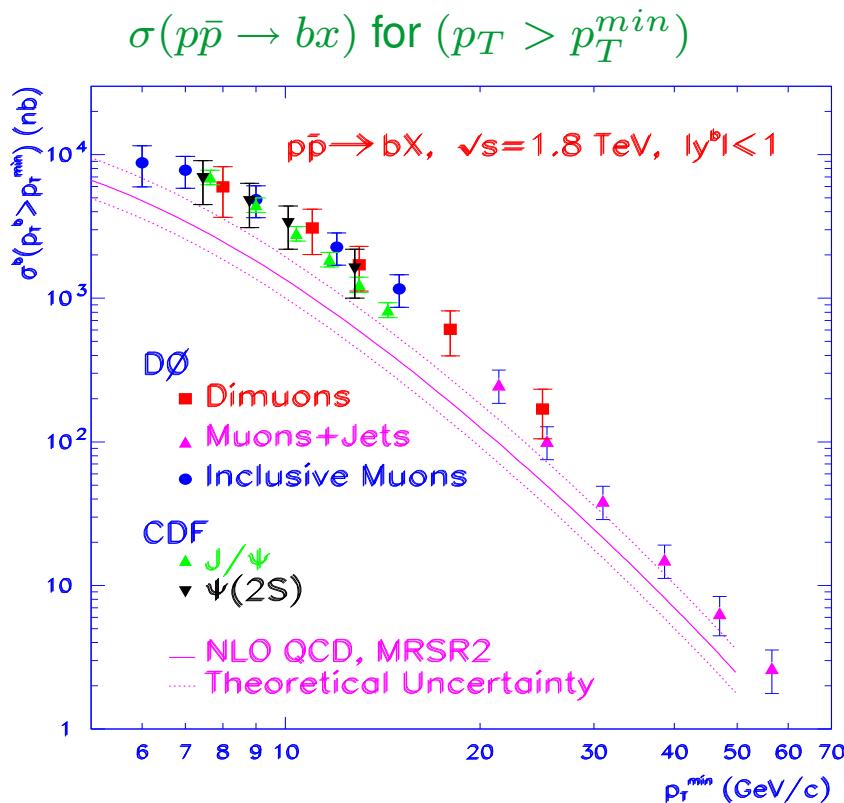
...MORE

"It now appears that there may be a fifth quark"



20 years later....

- In 1997, b production cross-sections were still $> 2 \times$ larger than QCD predictions. At that time only a small portion of the b hadron inclusive cross-section, $p_T > 6.0 \text{ GeV}/c$, had been measured.



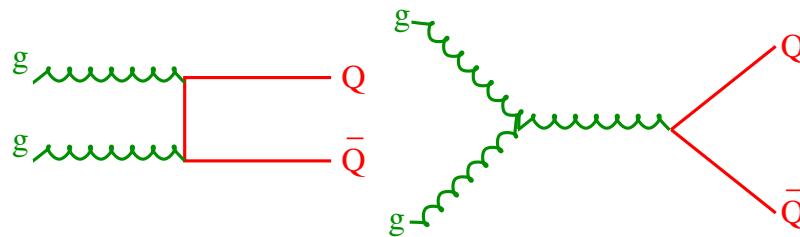
Is this a shape or normalization problem? What about *charm*?

Outline

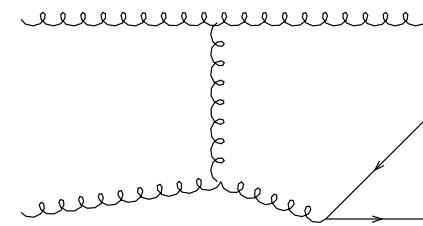
- Recent advances in the theory of heavy quark production cross-sections in $p\bar{p}$ collisions.
- Run II measurement of the *inclusive central J/ψ* cross-section down to $p_T = 0$ ($|y| < 0.6$) (CDF) and $|y| < 1.8$ ($p_T > 5 \text{ GeV}/c$) (D0).
- Run II measurement of the *inclusive central b-hadron* cross-section *using $b \rightarrow J/\psi X$* down to $p_T = 0$.
- Run II measurement of the charm-meson cross-sections.
- Other Run II production tidbits:
 - *confirmation of Belle's $X(3870) \rightarrow J/\psi \pi\pi$.*
 - *Run II high p_T b-jet production*
 - *Quarkonia production* (including diffractive!)

THE THEORY

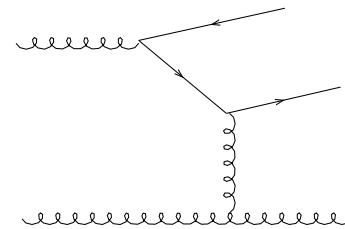
Heavy Quark Production in $p\bar{p}$



LO Heavy Quark Production



NLO: Gluon splitting



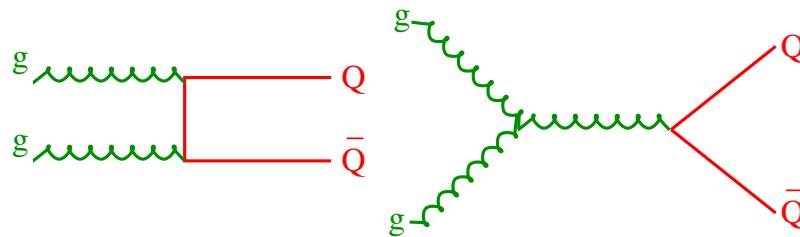
NLO: Flavour excitation

Factorization theorem: factorize physical observable into a calculable part and a non-calculable but universal piece:

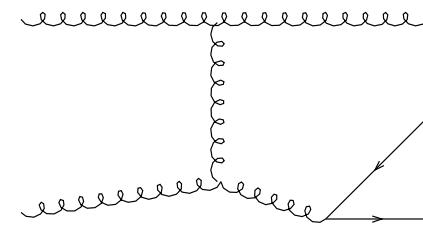
$$\frac{d\sigma(qq/gg/qg \rightarrow bX)}{dp_T(b)}$$

$\underbrace{\hspace{10em}}$
NLO/NNLO QCD

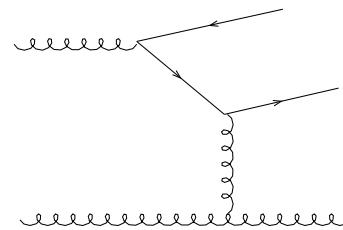
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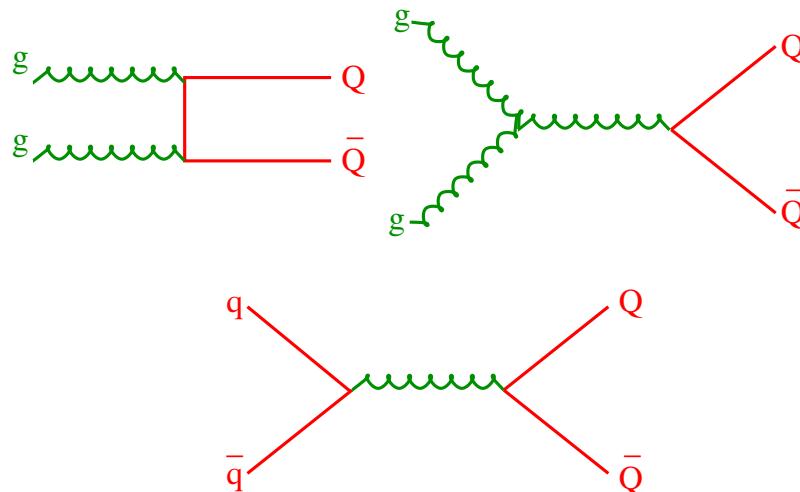


NLO: Flavour excitation

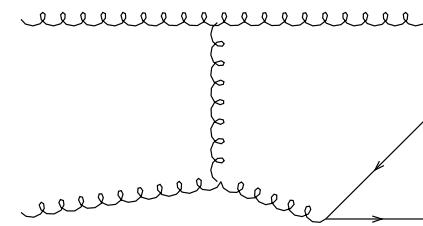
Factorization theorem: factorize physical observable into a calculable part and a non-calculable but universal piece:

$$\underbrace{\frac{d\sigma(qq/gg/qg \rightarrow bX)}{dp_T(b)}}_{\text{NLO/NNLO QCD}} \otimes \underbrace{f^{p,\bar{p}}}_{\text{Proton structure}}$$

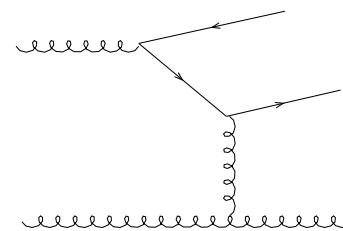
Heavy Quark Production in $p\bar{p}$



LO Heavy Quark Production



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NLO: Flavour excitation

Factorization theorem: factorize physical observable into a calculable part and a non-calculable but universal piece:

$$\underbrace{\frac{d\sigma(qq/gg/qg \rightarrow bX)}{dp_T(b)}}_{\text{NLO/NNLO QCD}} \otimes \underbrace{f^{p,\bar{p}}}_{\text{Proton structure}} \otimes \underbrace{D^{b \rightarrow B}}_{\text{fragmentation}} = \underbrace{\frac{d\sigma(p\bar{p} \rightarrow BX)}{dp_T(B)}}_{\text{observed}}$$

Probing proton structure, $f^{p,\bar{p}}$

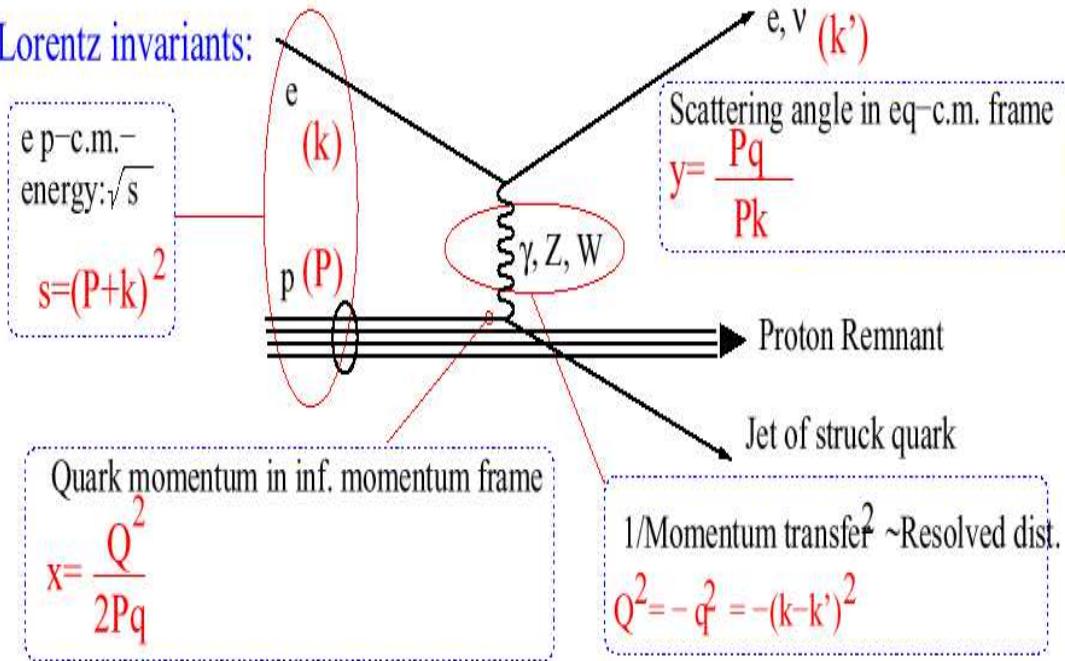
$e/\mu/\nu$ used to probe Proton Structure:

Reactions:

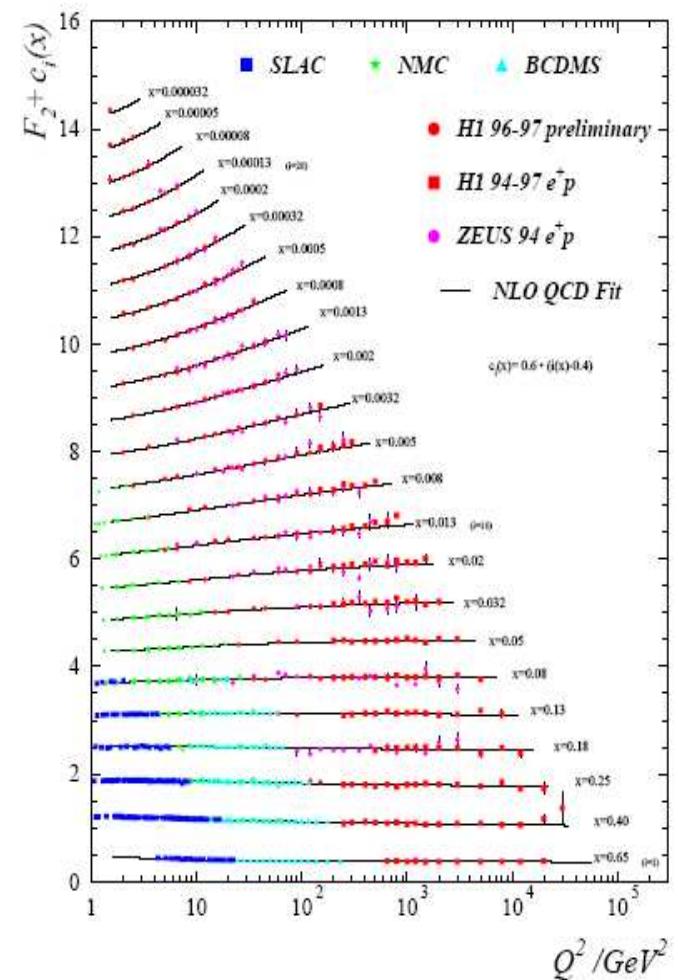
NC: $e + p \rightarrow e + X$

CC: $e + p \rightarrow \gamma + X$

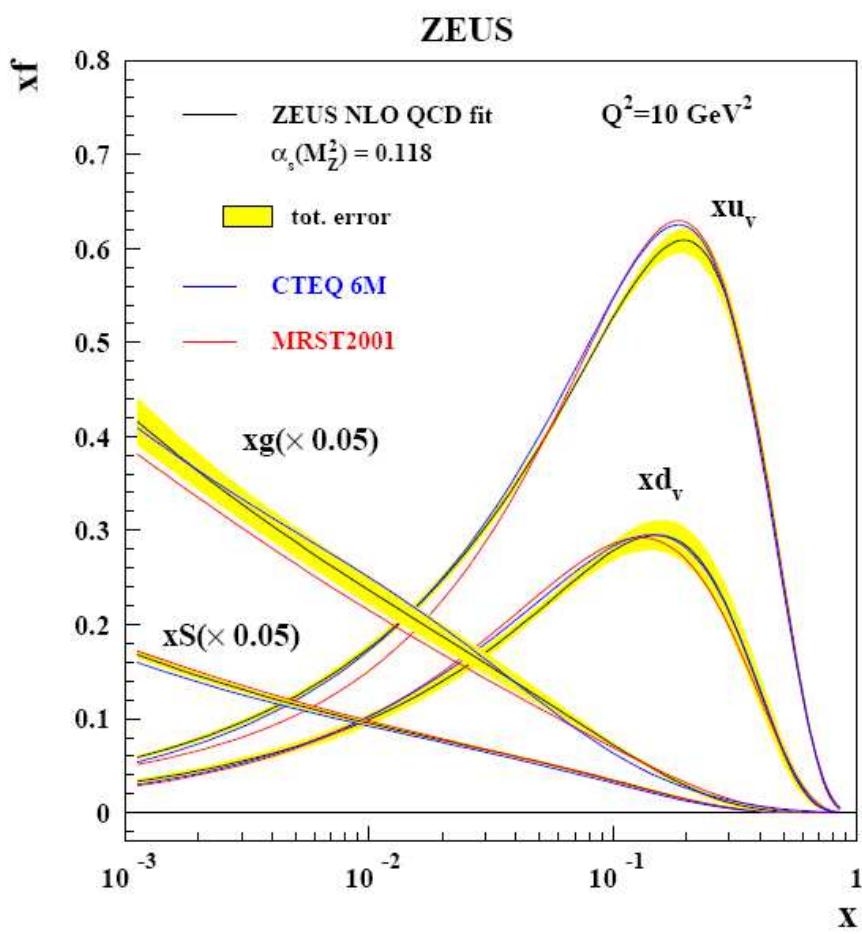
Lorentz invariants:



Relation: $Q^2 = s \times y$ ($M_p \ll P$)

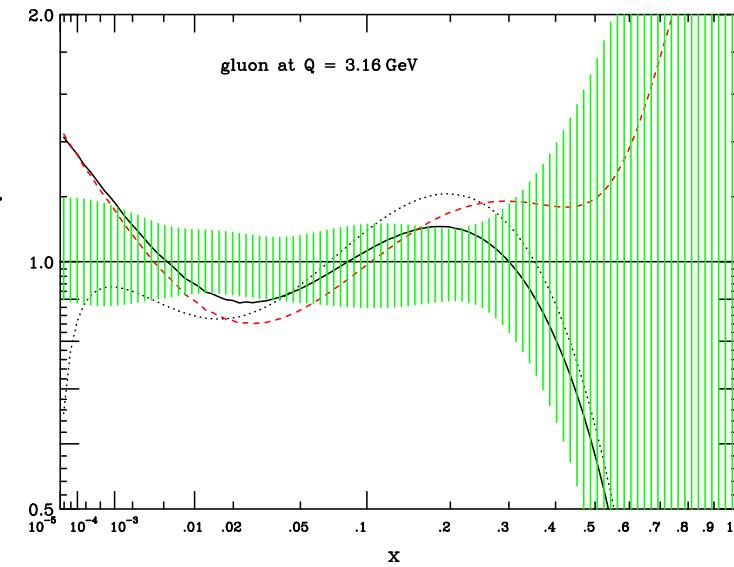


Parton Density Functions (PDF)



Parton densities with uncertainties extracted
from fits to the data

- PDFs ($x f(x, Q^2)$) are universal global fits to data on proton structure that are independent of the measurement process.

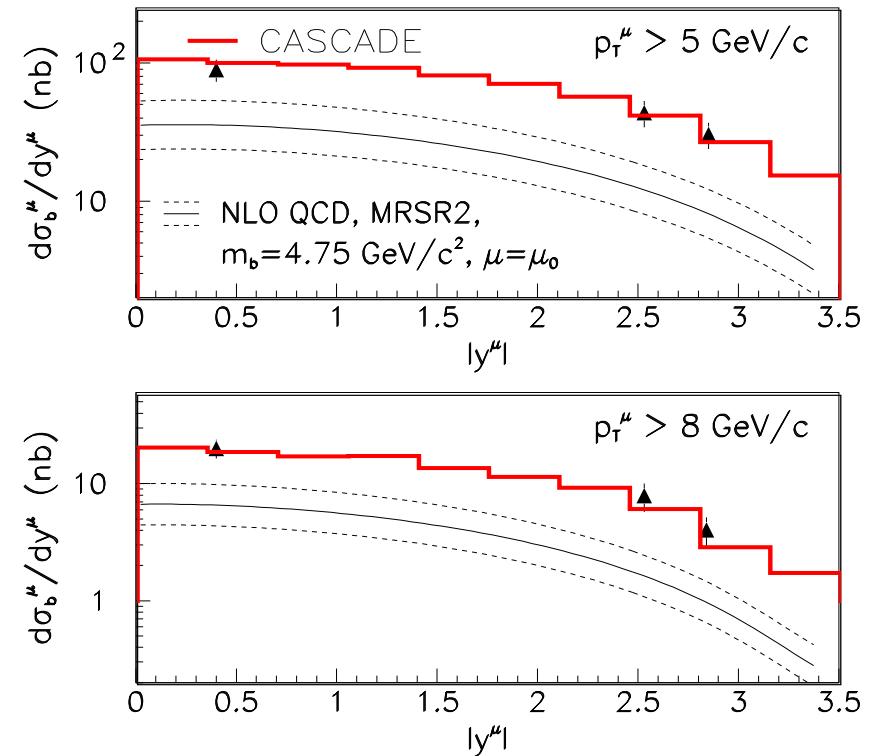
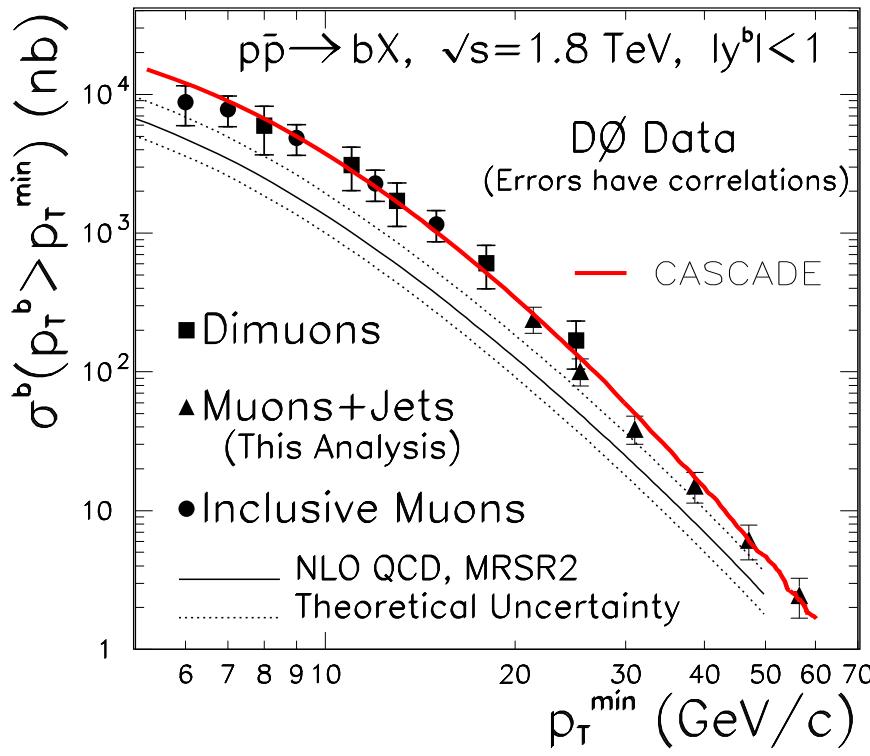


Uncertainties on gluonic function

2001: k_T Factorization Scheme

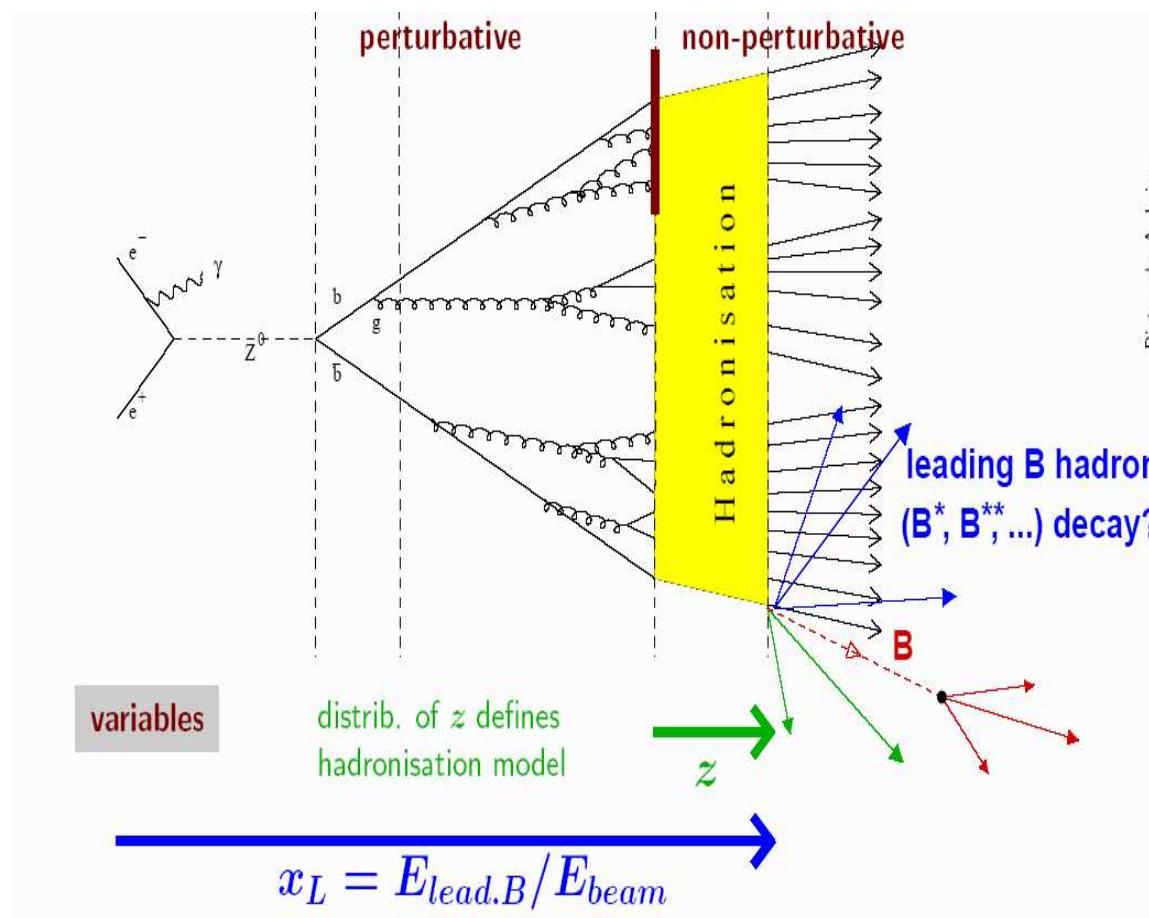
Standard PDFs are functions of x , the fraction of the momentum carried by the parton longitudinal to the hadron direction. Partons also have a small transverse momentum component:

k_T factorization : $f(x) \rightarrow f(x, k_T)$, $\sigma(x, s) \rightarrow \sigma(k_T, x, s)$

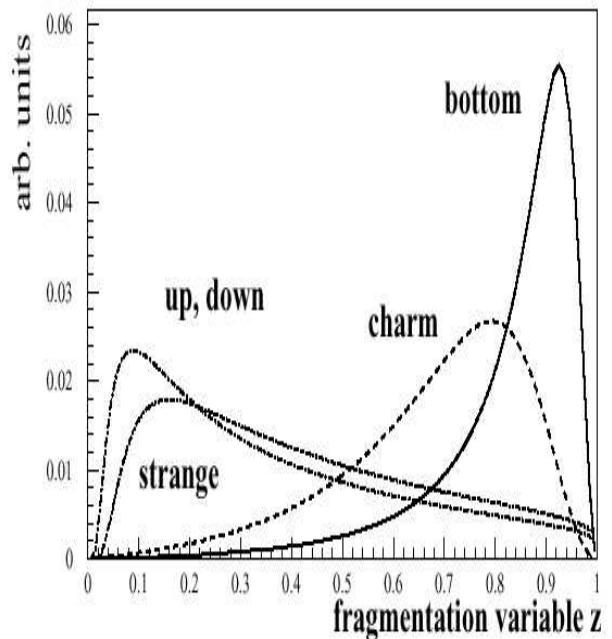


Fragmentation Functions $D^{b \rightarrow B}$

$$D^{meas}(x) = \int \underbrace{D^{pert}(x')}_{pQCD/MC} \otimes \underbrace{D^{non-pert}(x')}_{Parameterized/MC} dx'$$



Peterson parameterization

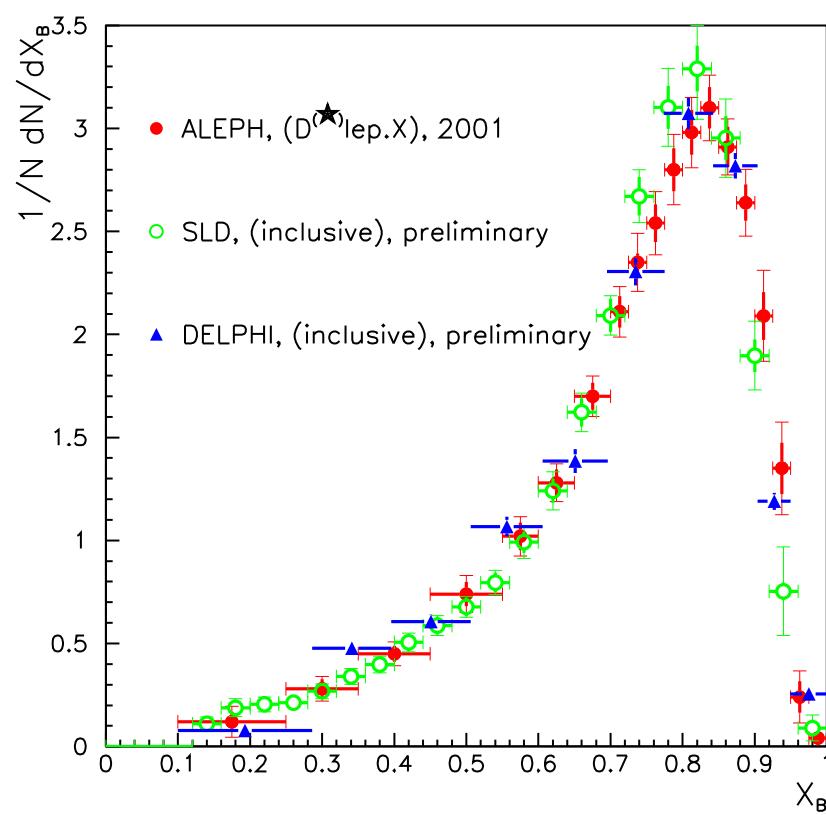


$$z = \frac{(E+p_{||})_{hadron}}{(E+p)_{quark}}$$

Recent Theory Advances

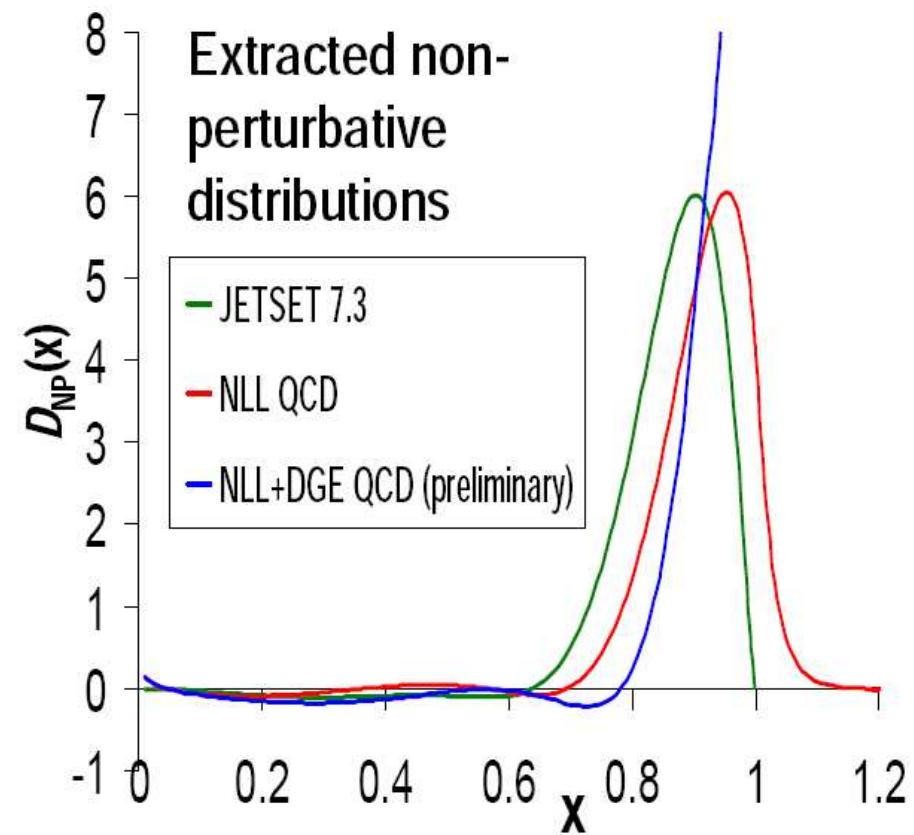
- In pQCD calculations where the quarks are treated as massive, powers of $\alpha_s \log p_T / m_Q$ modify **shape** of fragmentation function:
 - $p_T \gg m_Q$: logarithms large \Rightarrow large corrections needed.
 - Next-to-Leading-log resummations performed in 2001.
 - *Important for predicting Tevatron heavy quark cross-section shapes at high p_T .*
- New approach: Moment analysis (Cacciari *et. al.* - 2002)
 - Transformation: $\tilde{D}(N) = \int x^{N-1} D(x) dx \rightarrow$ moment space
 - $\tilde{D}^{meas}(N) = \underbrace{\tilde{D}^{pert}(N) \times \tilde{D}^{non-pert}(N)}_{\text{A product}}$

Measured Fragmentation Fncns.



$D(x)$ Measured

E. Ben Haim *et. al.* hep-ph/0302157

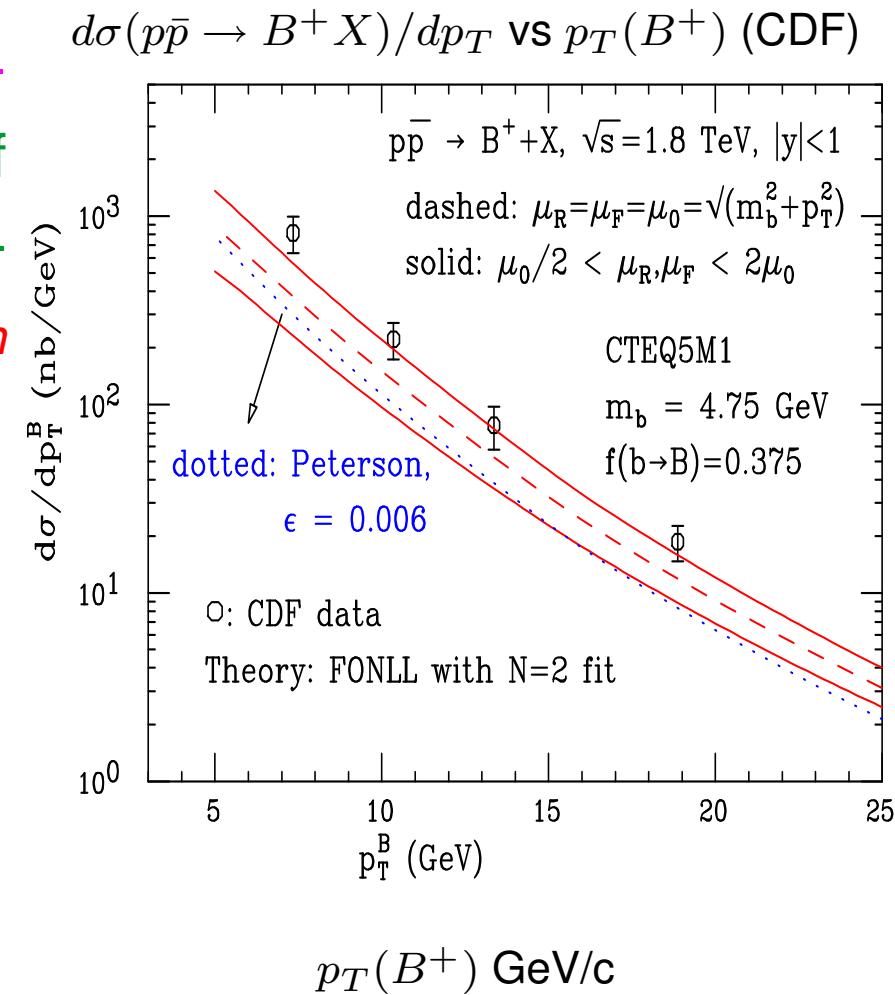
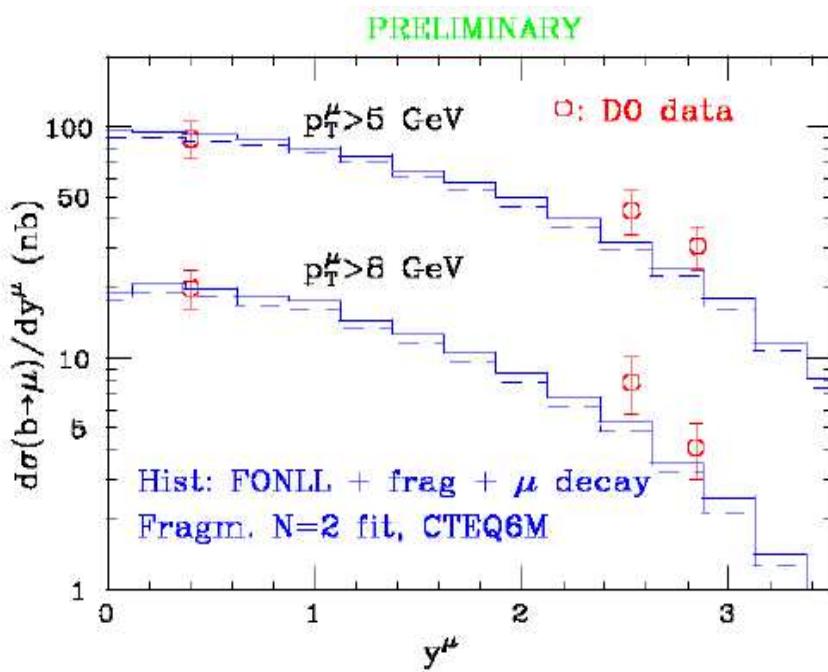


$D^{non-pert}(x')$ Extracted

Non-perturbative functions used must match perturbative assumptions

Comparison with Run I Data - NLL

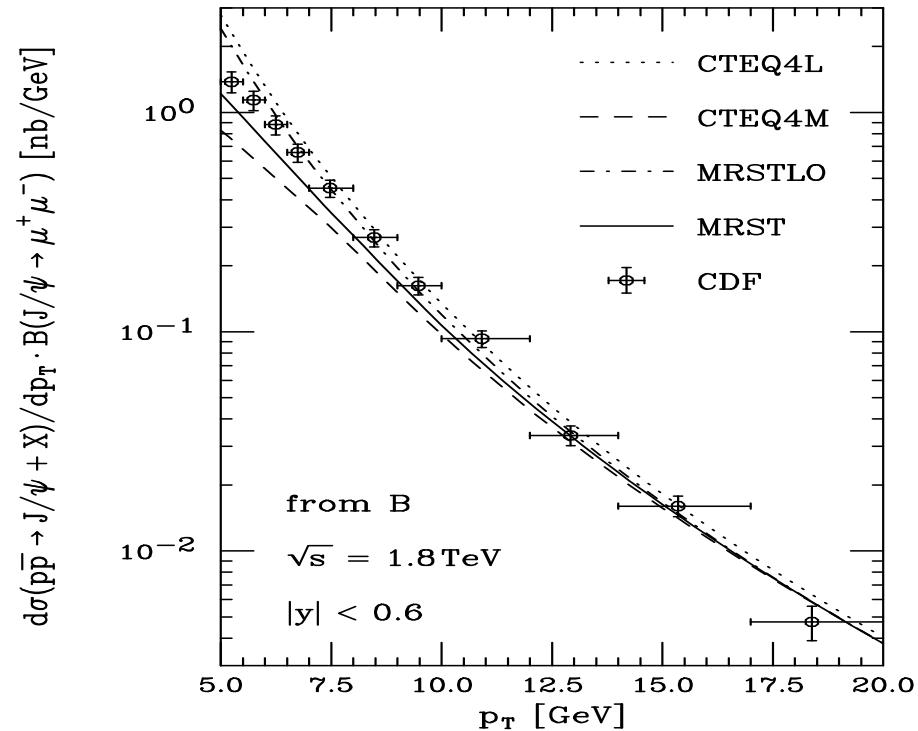
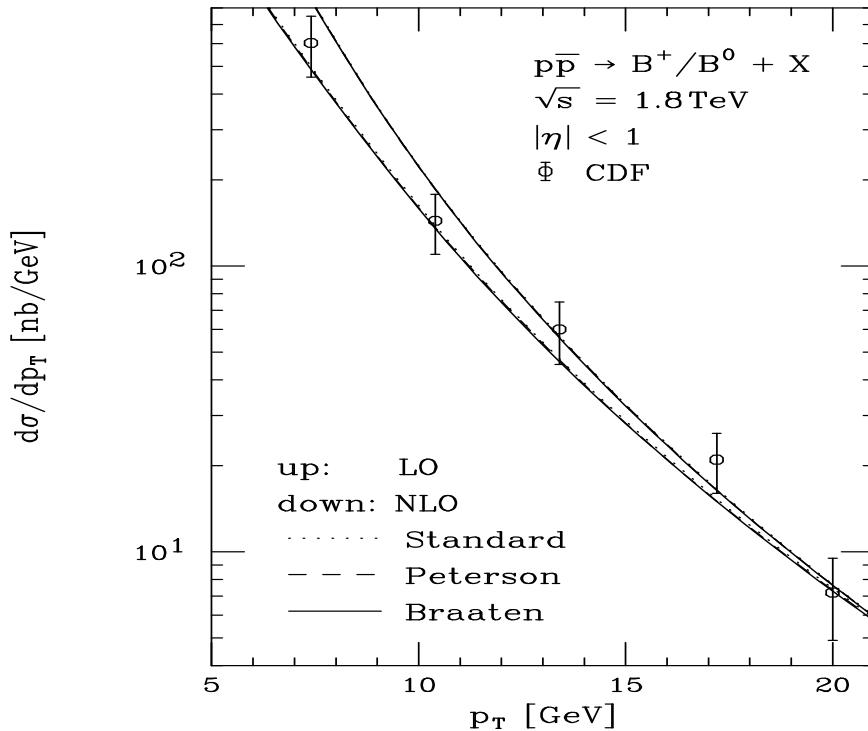
Fixed order (FO) QCD NLO calculation + Resummation of next-to-leading logs (NLL). Method of moments instead of a fragmentation model \Rightarrow Better agreement with CDF and D0 Run I data



Cacciari, Nason hep-ph/0204025 (Run I)

Alternatives to FONLL

Non-perturbative fragmentation functions for B mesons are extracted from recent LEP data using 3 different parameterizations. used with \bar{MS} factorization scheme where quarks are treated as massless (no NLL needed).



Binnewies, Kniehl, Kramer hep-ph/9802231 (Run I)

hep-ph/9901348 (Run I)

Only works for $M_H \gg Q$ and is not valid for $M_H \sim Q$

Theory Summary

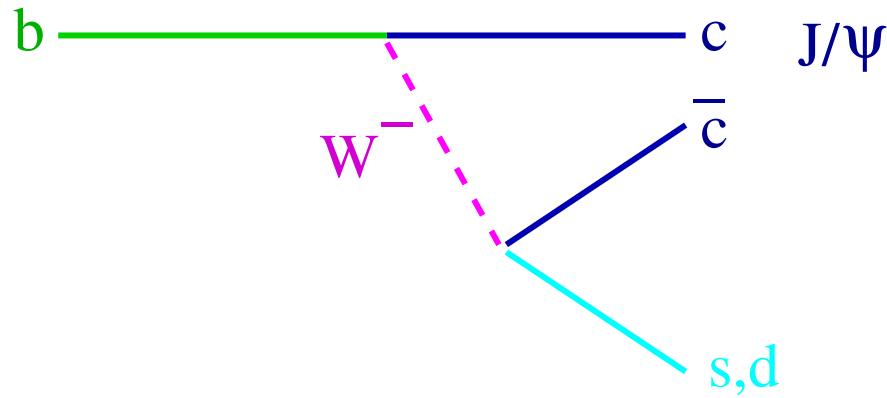
- Agreement with the Run I b cross-section data for $p_T > 5.0$ GeV/c has greatly improved without the need to invoke exotic sources of excess b quarks. Most of the improvement is due to improved treatment of experimental inputs.
- BUT: Different theoretical approaches: different factorization schemes, FONLL calculations, new methods to extract the non-perturbative part of fragmentation function. Which is the correct approach?

Total cross-sections do not depend on the fragmentation model!

= powerful experimental test of QCD calculations.

**Charm quark mass and production cross-sections are close to b -quark
but fragmentation is very different - test theory predictions**

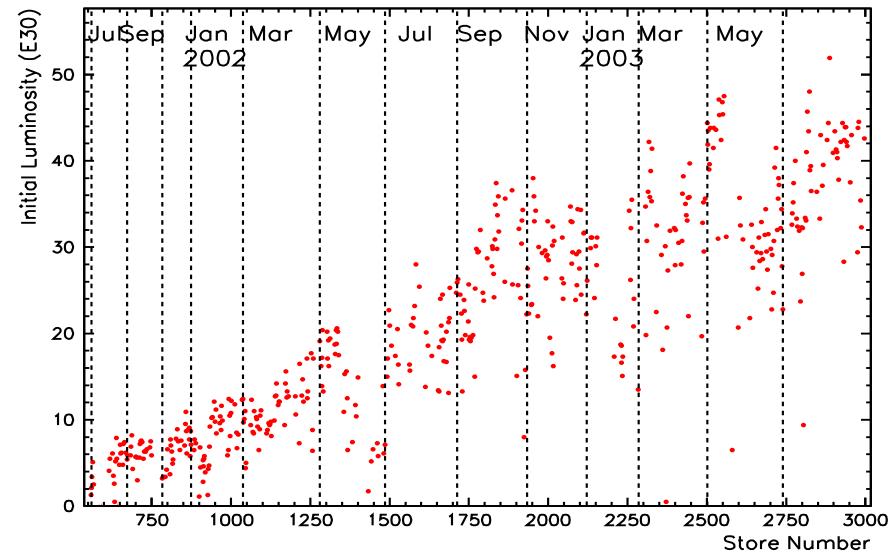
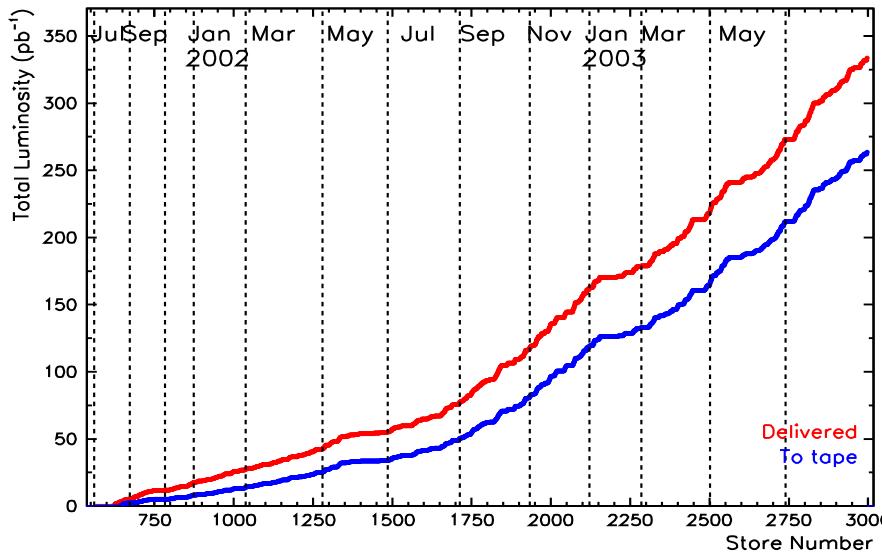
RUN II MEASUREMENT OF THE J/ψ AND b -HADRON INCLUSIVE CROSS-SECTIONS



The Tevatron Today

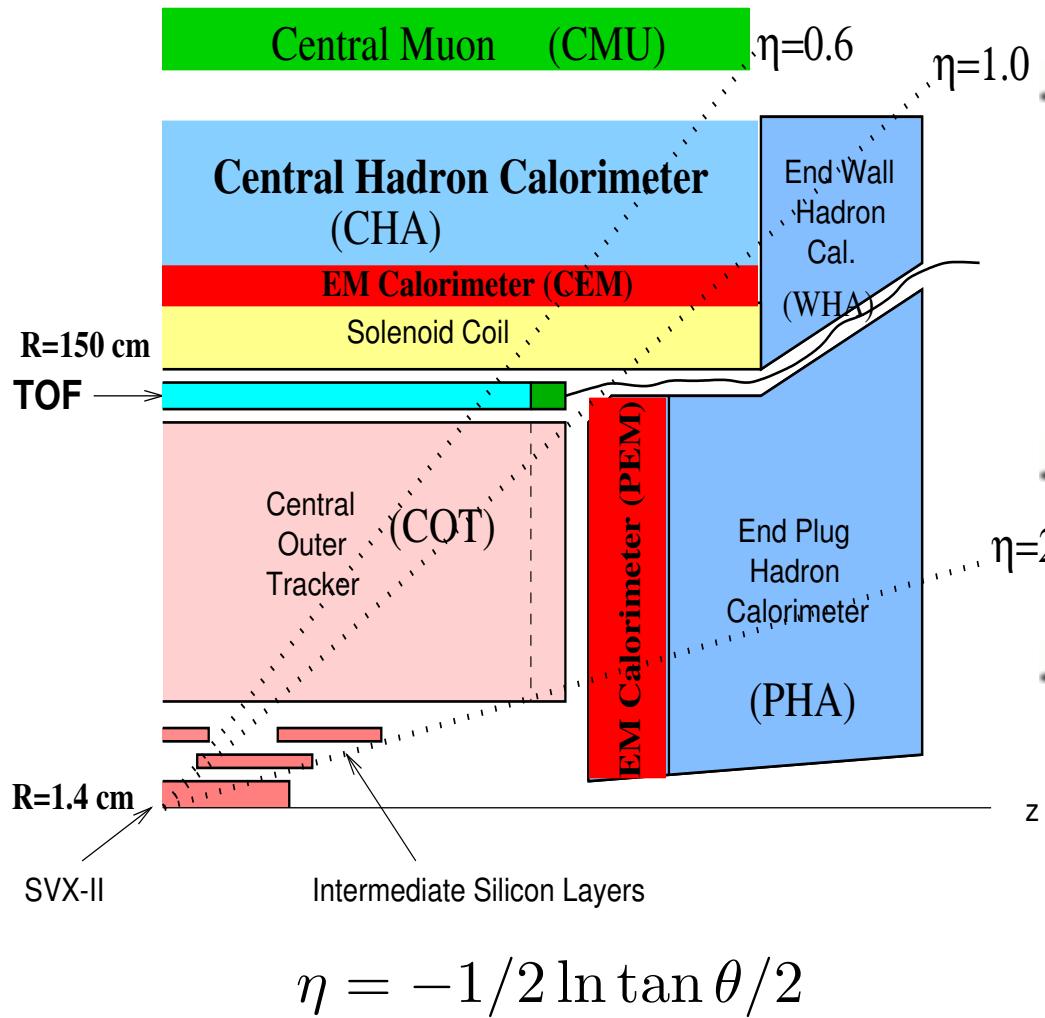
- In 1985, Tevatron collider begins operating @ $\sqrt{s} = 1.6 \text{ TeV}$
- Run I of the Tevatron collected collider data at $\sqrt{s} = 1.8 \text{ TeV}$ from 1992-1995. $\sim 109 \text{ pb}^{-1}$ of data was collected by the 2 collider detectors with $\mathcal{L}^{typical} = 1.6 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$

Run II : Summer 2001 - present. 2.5X more data already!



CDF Run II - Overview

Signals: $J/\psi \rightarrow \mu\mu$, $D \rightarrow K\pi$, displaced b vertices



- **Central Muon detector**: Prop. chambers outside central calor. $\sim 5\pi$ interaction lengths.

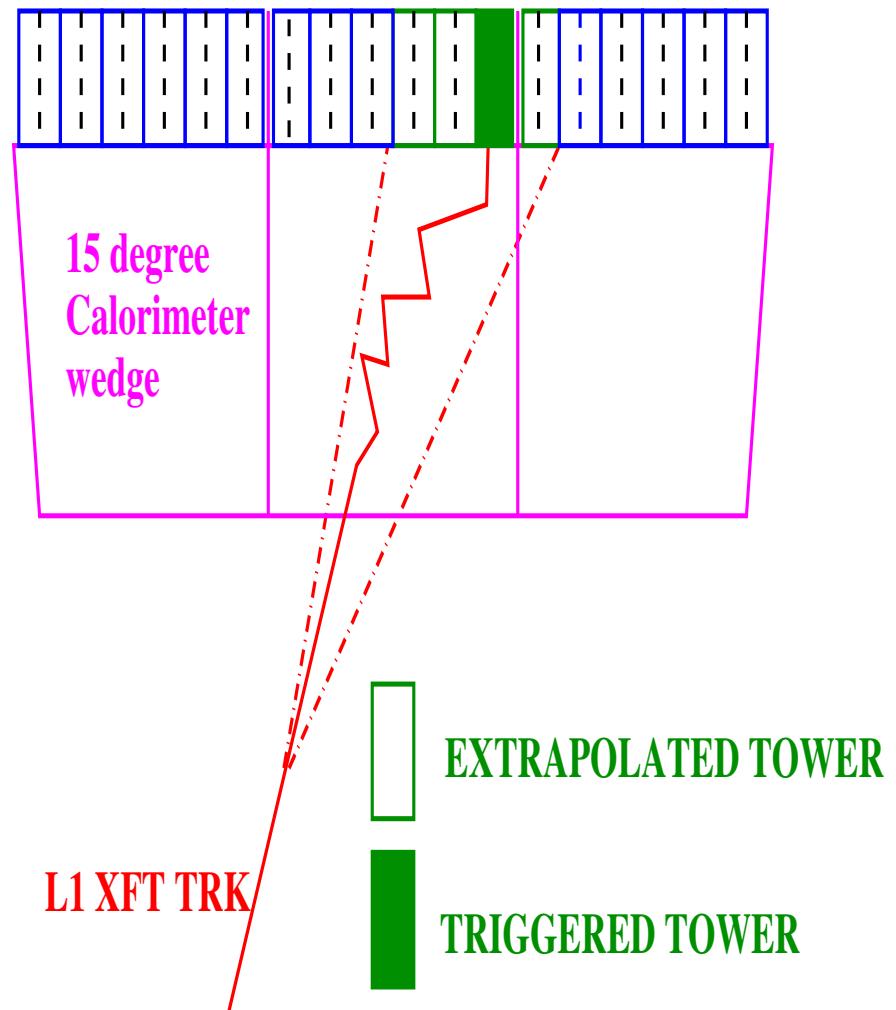
- **96 layer COT**:

$$\sigma(p_t)/p_t = 0.003p_t$$

- **Silicon vertex detector**: 8 Layers of 3-D Silicon up to $|\eta| = 2$, 700,000 readout channels, $\sigma(d_0) \sim 20\mu\text{m}$

L1 Muon triggers (CDF)

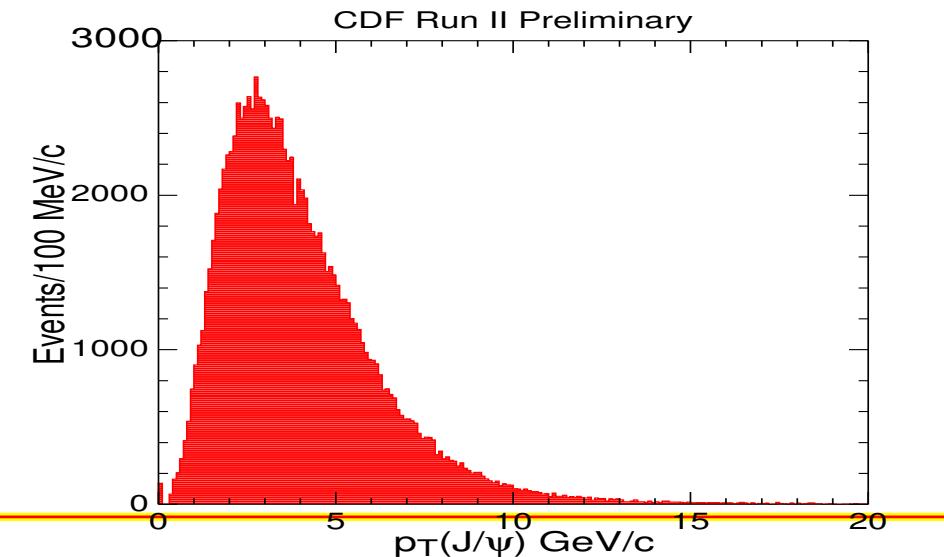
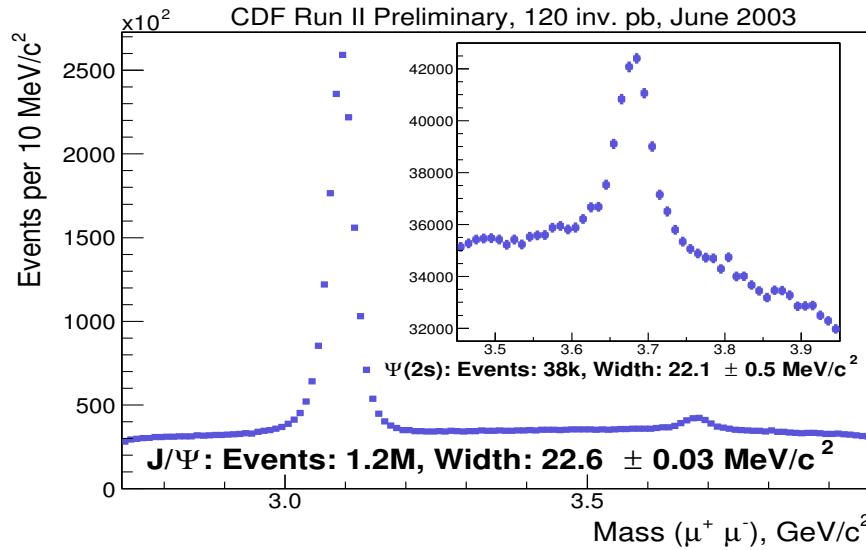
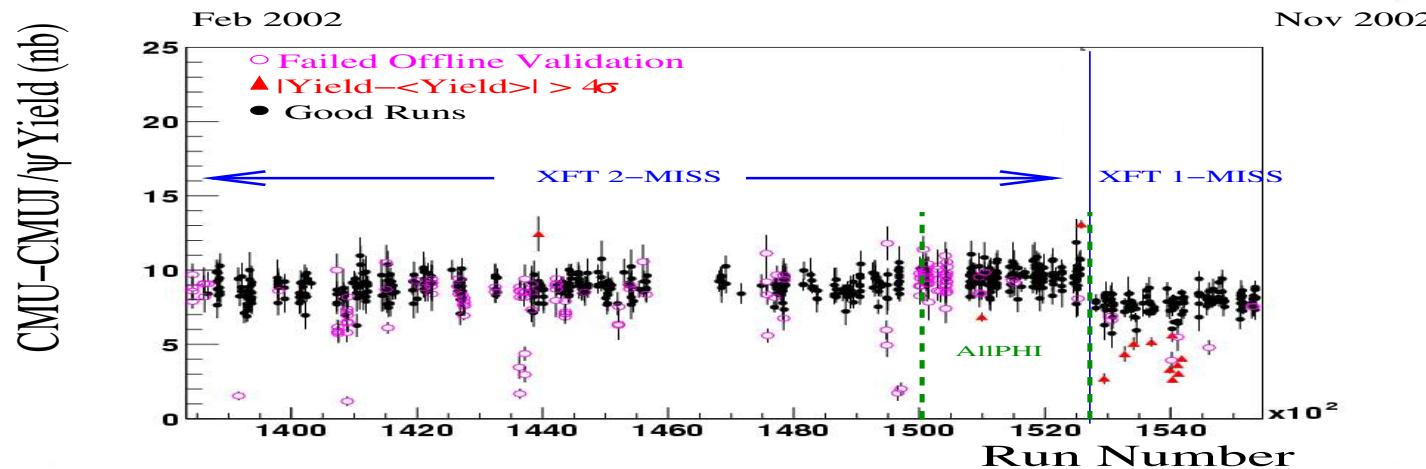
- Tracks are reconstructed in the COT by the Level 1 Trigger eXtra Fast Tracker (XFT). A match is made to hits in the Central Muon Chambers.



Can now reach $p_t(J/\psi) = 0 \text{ GeV}/c$.

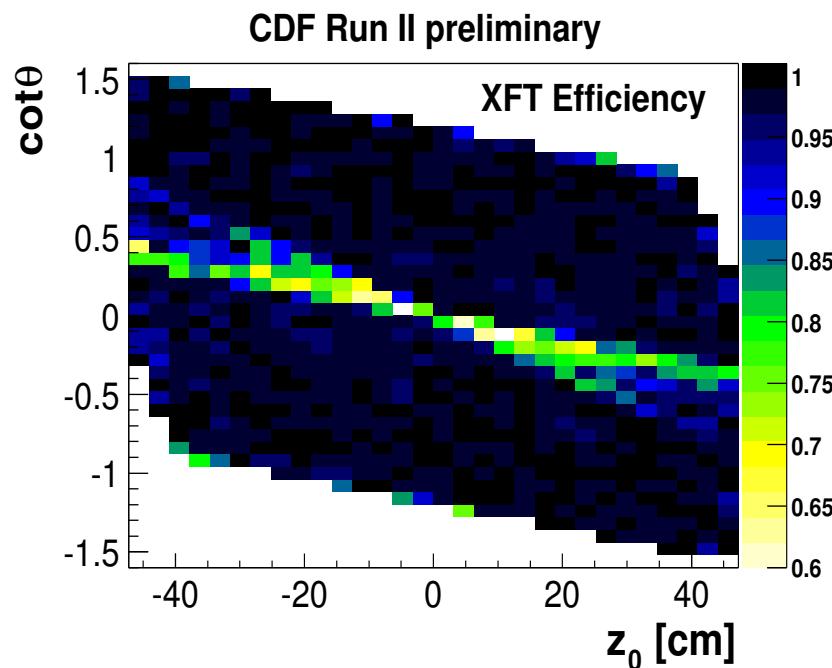
L1 Muon Trigger performance

Trigger stable and accepting central J/ψ at a rate of 9/nb⁻¹



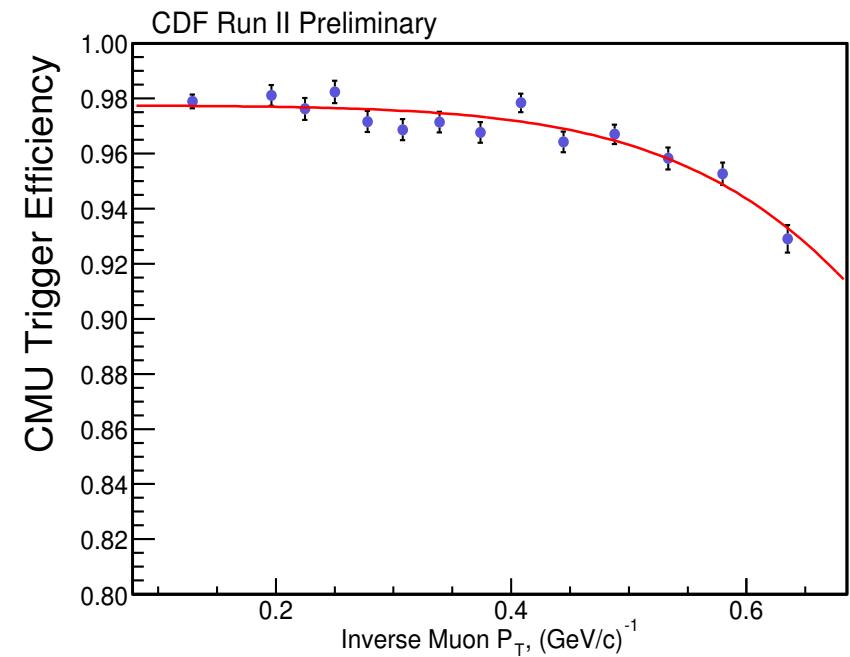
L1 Muon Trigger efficiency

XFT tracking efficiency



Inefficient near center of wire planes

L1 muon trigger efficiency .vs. $1/p_T$

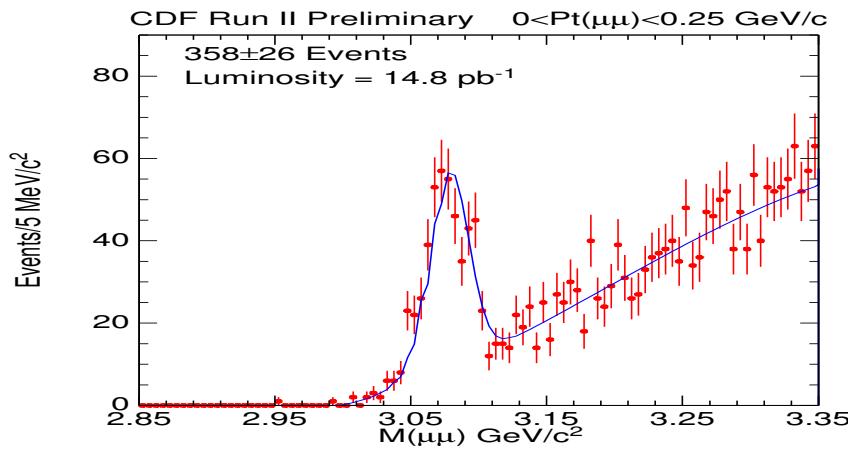


After excluding XFT inefficient region

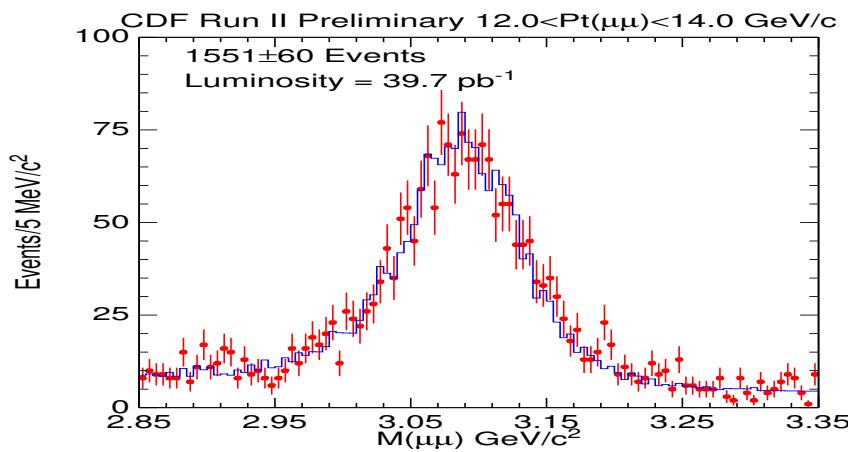
- Level 1 single μ trigger efficiency at 1.5 GeV/c is 92%
- Plateau is at 98 % except for tracks passing within 1.5 cm of the center of the COT wire plane where spacers are located

J/ψ Reconstruction/Acceptance

Dimuon Mass Distributions

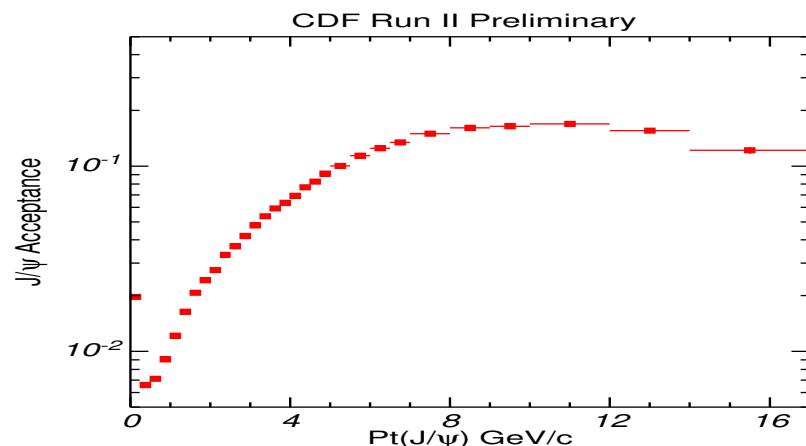


$0 < p_T(J/\psi) < 0.25 \text{ GeV}/c$

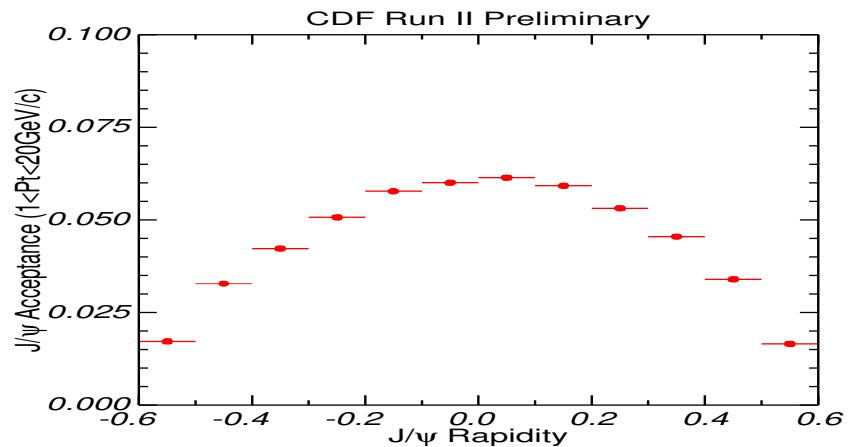


$12 < p_T(J/\psi) < 14 \text{ GeV}/c$

Detector acceptance (MC)



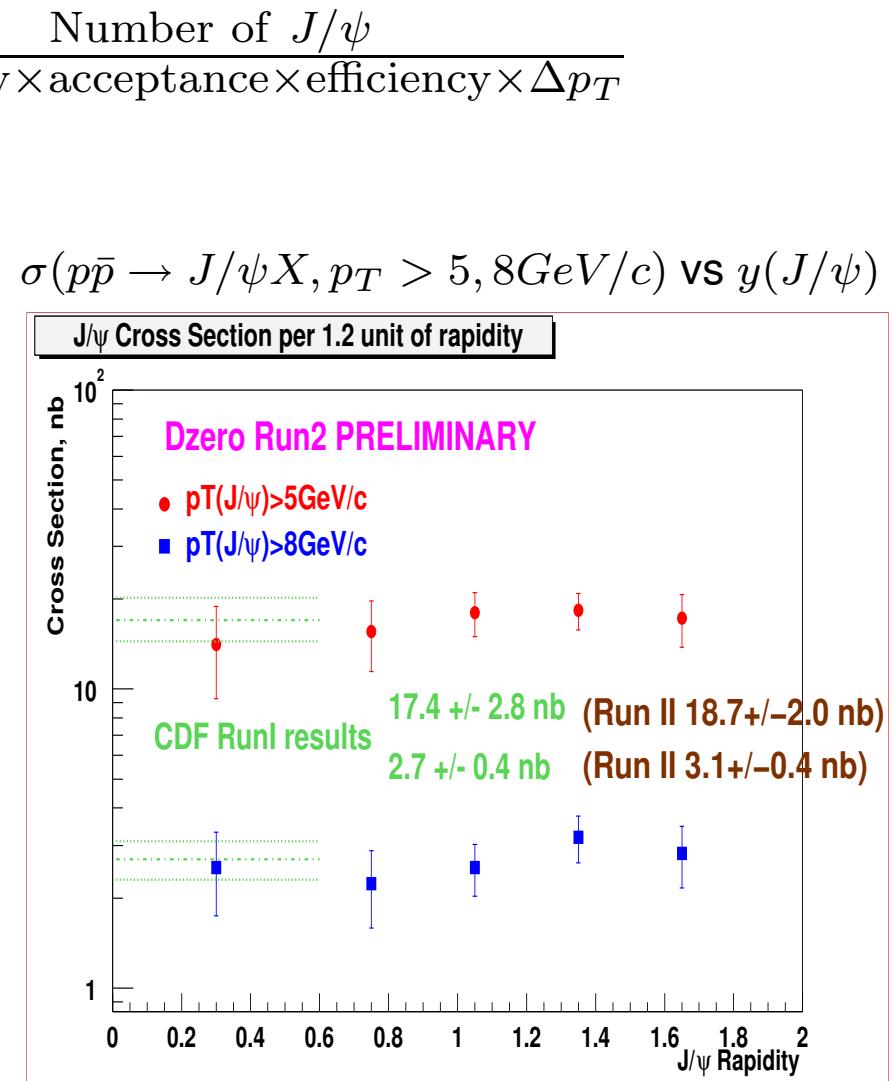
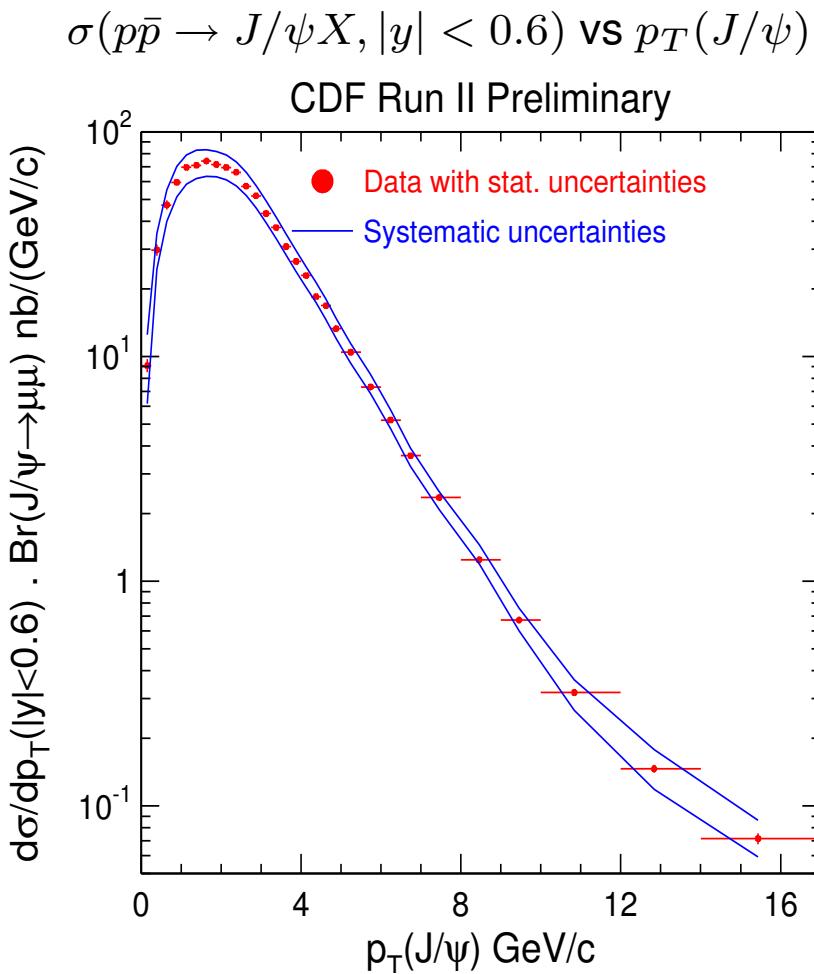
Transverse momentum



Rapidity

J/ψ Cross-sections - Run II

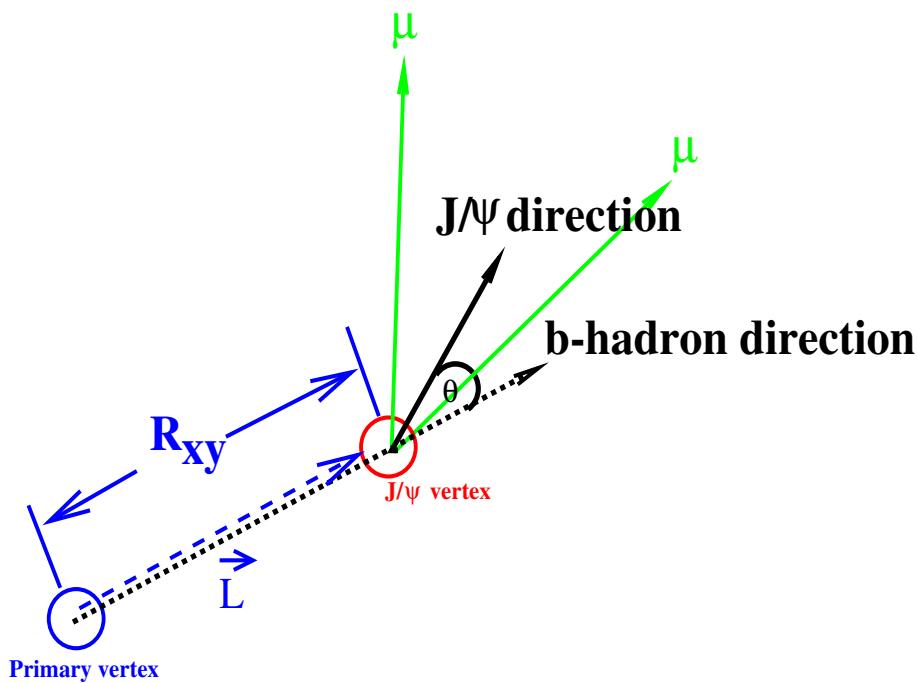
$$\frac{d\sigma(p\bar{p} \rightarrow J/\psi X)}{dp_T(J/\psi)} = \frac{\text{Number of } J/\psi}{\text{luminosity} \times \text{acceptance} \times \text{efficiency} \times \Delta p_T}$$



$\sigma(p\bar{p} \rightarrow J/\psi X, |y(J/\psi)| < 0.6) = 4.08 \pm 0.02(\text{stat})^{+0.60}_{-0.48}(\text{syst}) \mu\text{b}$

Separate $H_b \rightarrow J/\psi X$ from Total

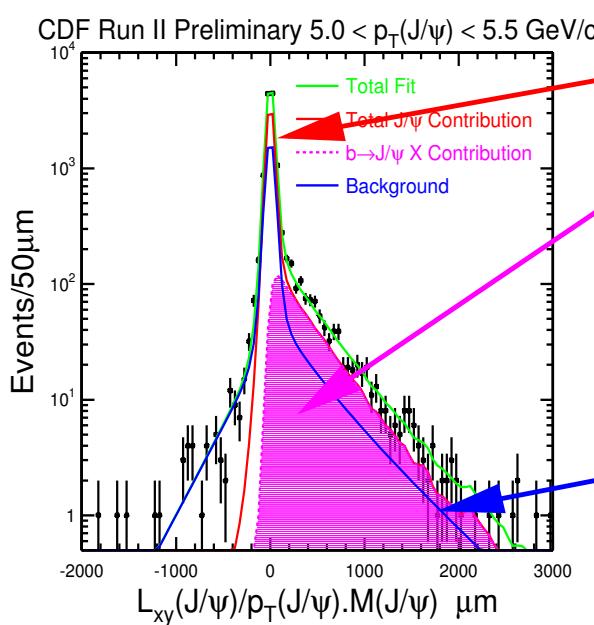
- The J/ψ inclusive cross-section includes contributions from
 - Direct production of J/ψ
 - Indirect production from decays of excited charmonium states such as $\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$
 - Decays of b -hadrons such as $B \rightarrow J/\psi X$



- b -hadrons have long lifetimes, J/ψ from $H_b \rightarrow J/\psi X$ will be displaced.

Extracting the b -fraction

- A maximum likelihood fit to the **flight path** of the J/ψ in the $r - \phi$ plane, L_{xy} is used to extract the **b -fraction**.

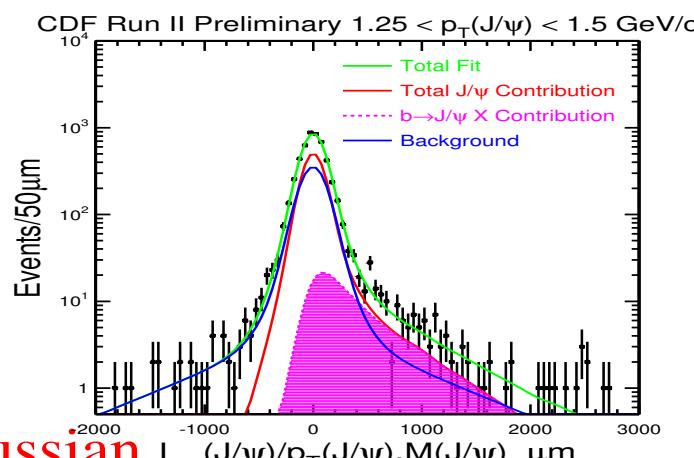


Prompt J/ψ
is a double Gaussian
= resolution function

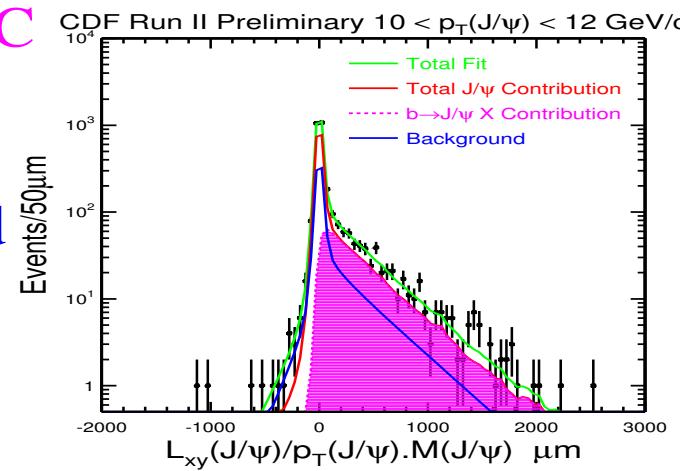
$b \rightarrow J/\psi X$
shape from MC
template

Parameterized
background

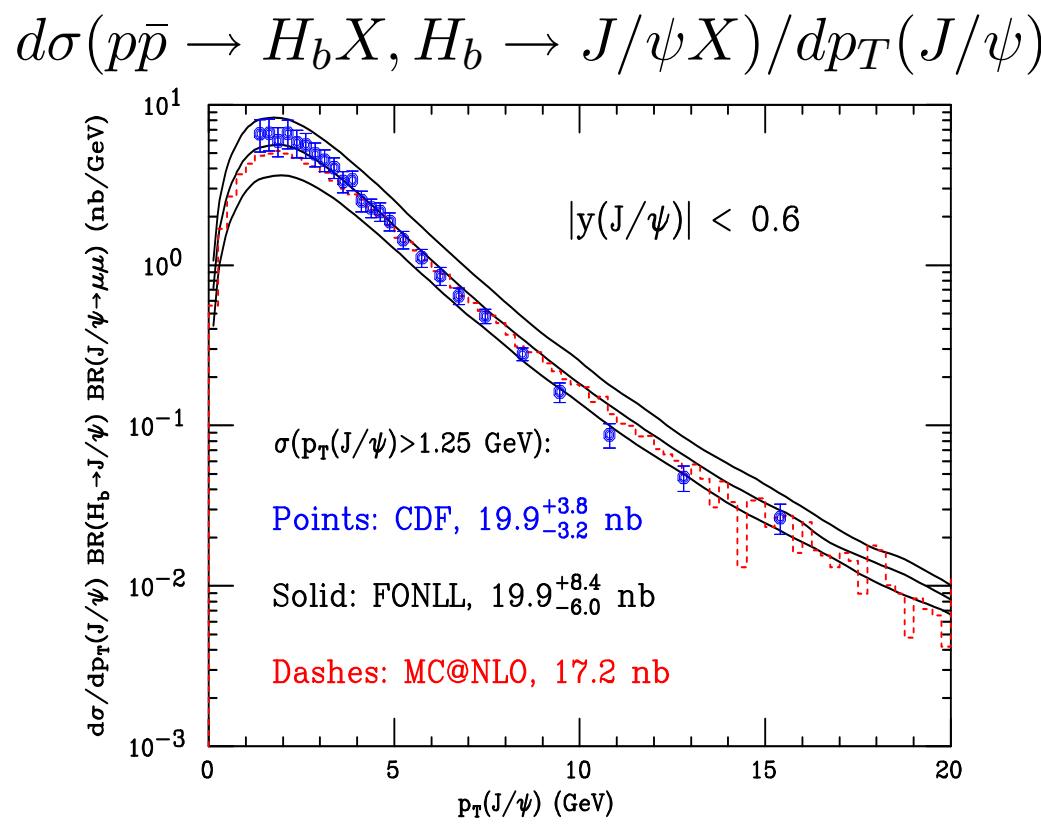
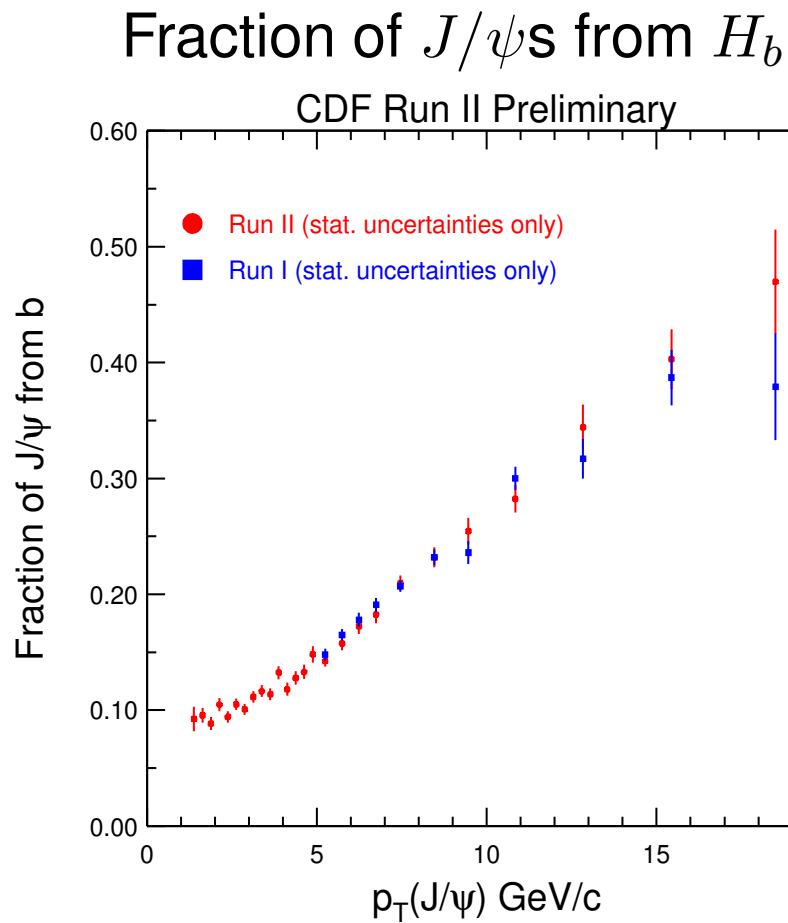
$1.25 < p_T < 1.5 \text{ GeV}/c, f_b = 9.7\%$



$10 < p_T < 12 \text{ GeV}/c, f_b = 28\%$



$$d\sigma(p\bar{p} \rightarrow H_b X)/dp_T(J/\psi)$$



Theory: M.Cacciari, S. Frixione, M.L. Mangano, P. Nason, G. Ridolfi (Dec, 2003)

MC@NLO : QCD NLO at 1.96 TeV, with the latest PDFs properly matched to tuned HERWIG shower MC for fragmentation (JHEP 0206:029, 2002)

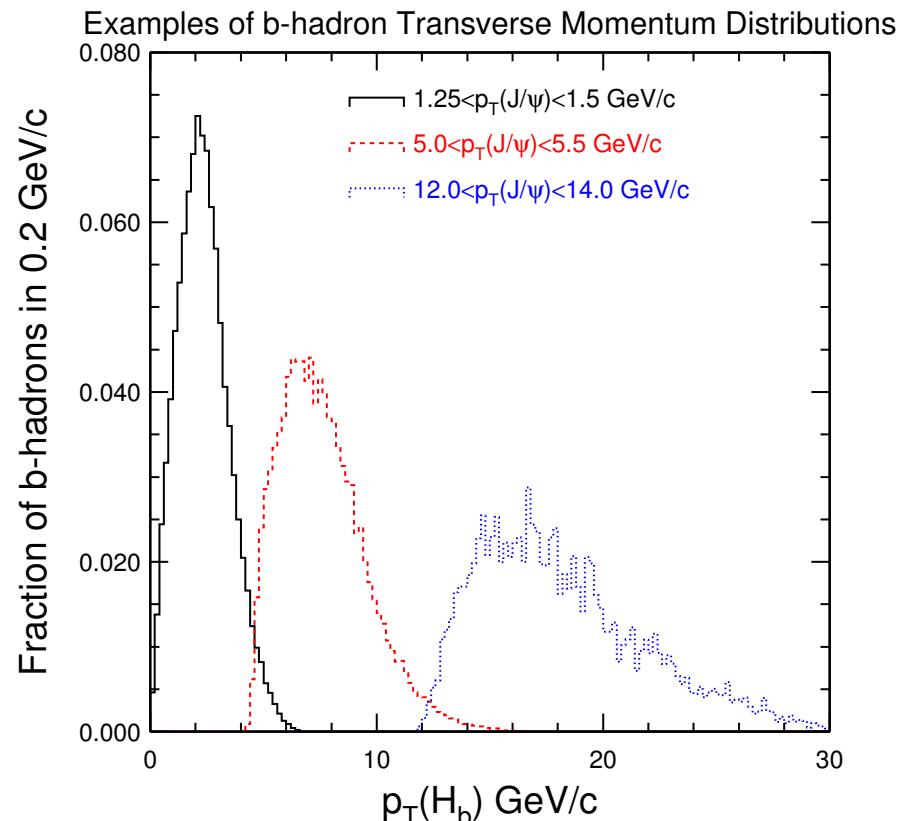
Algorithm to extract $d\sigma/dp_T(H_b)$

- Count the observed number of b -hadrons in a given $p_T(H_b)$ bin

$$N_i^b = \sum_{j=1}^N w_{ij} N_j^{J/\psi}$$

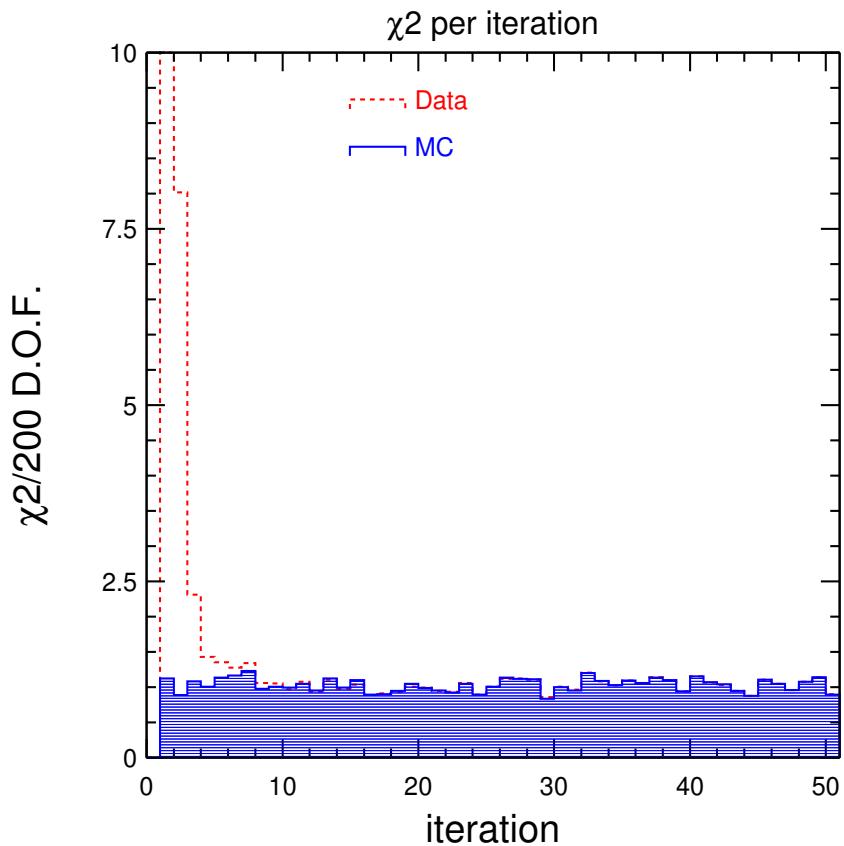
w_{ij} is the fraction of b events in the i^{th} $p_T(H_b)$ from the j^{th} $p_T(J/\psi)$ bin obtained from MC.

- Correct the observed number of b -hadrons for the kinematic acceptance



Iterating...

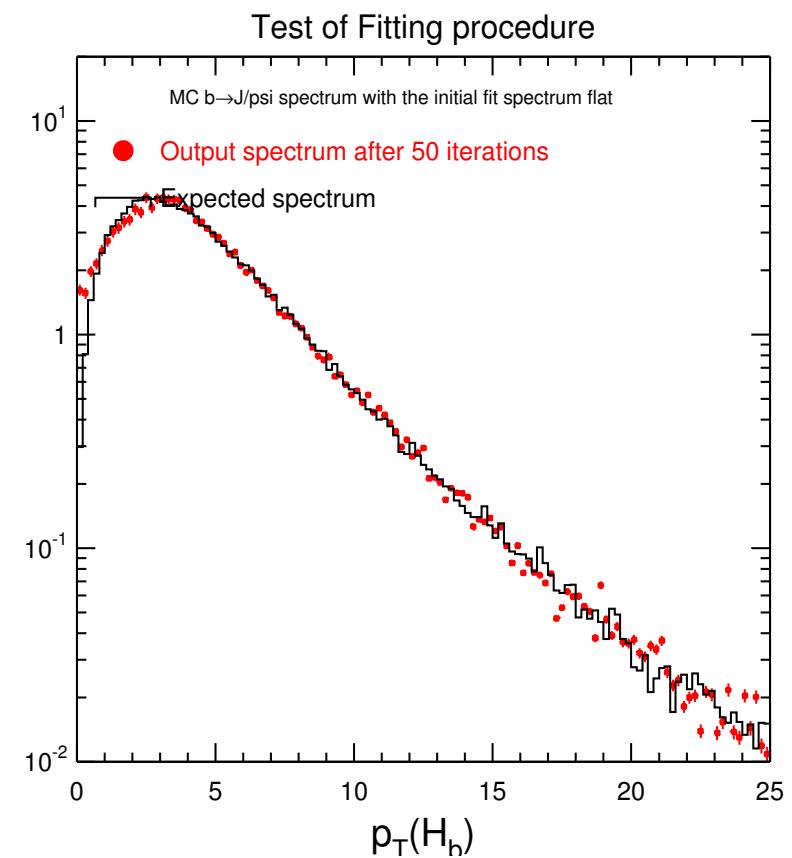
- After a $d\sigma/dp_T(H_b)$ spectrum is obtained, the MC weights w_{ij} are recomputed using the new spectrum and the algorithm repeated.
- A χ^2 test is performed on the input and output spectra until no difference is seen.



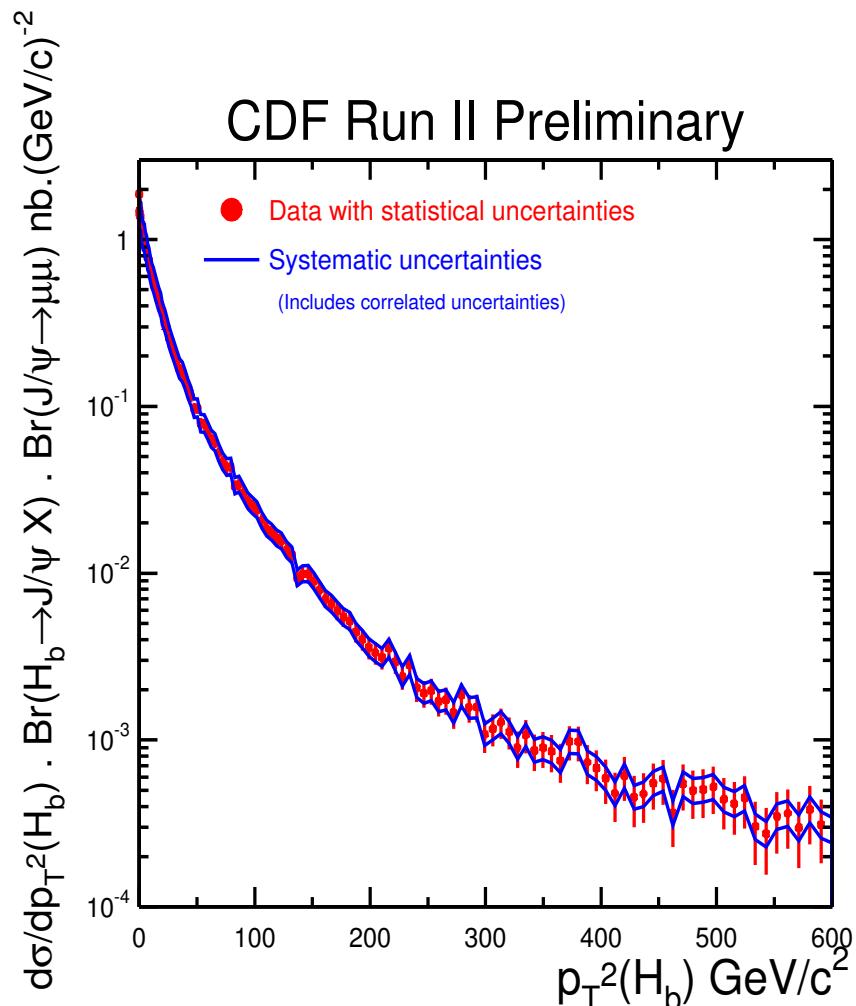
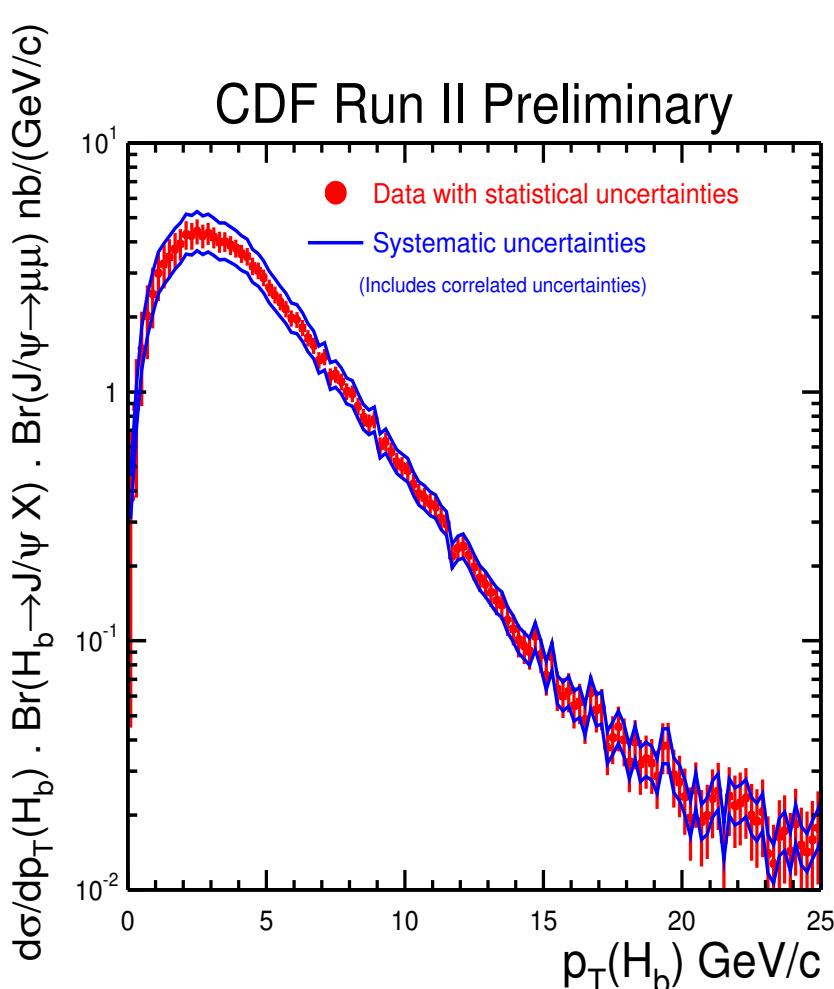
Proof of Principle

- We test the algorithm using the $d\sigma/dp_T(J/\psi)$ distribution from a MC sample with a *known distribution* of $d\sigma/dp_T(H_b)$ similar to the data.
- An *independent* MC sample, generated with a flat $d\sigma/dp_T(H_b)$ spectrum, is used to compute the weights w_{ij}

The correct spectrum is extracted.



The inclusive H_b cross-section



Since each H_b contains a bottom quark, correcting for branching fractions we get:

$$\sigma(p\bar{p} \rightarrow \bar{b}X, |y| < 1.0) = 29.4 \pm 0.6(\text{stat}) \pm 6.2(\text{syst}) \mu\text{b}$$

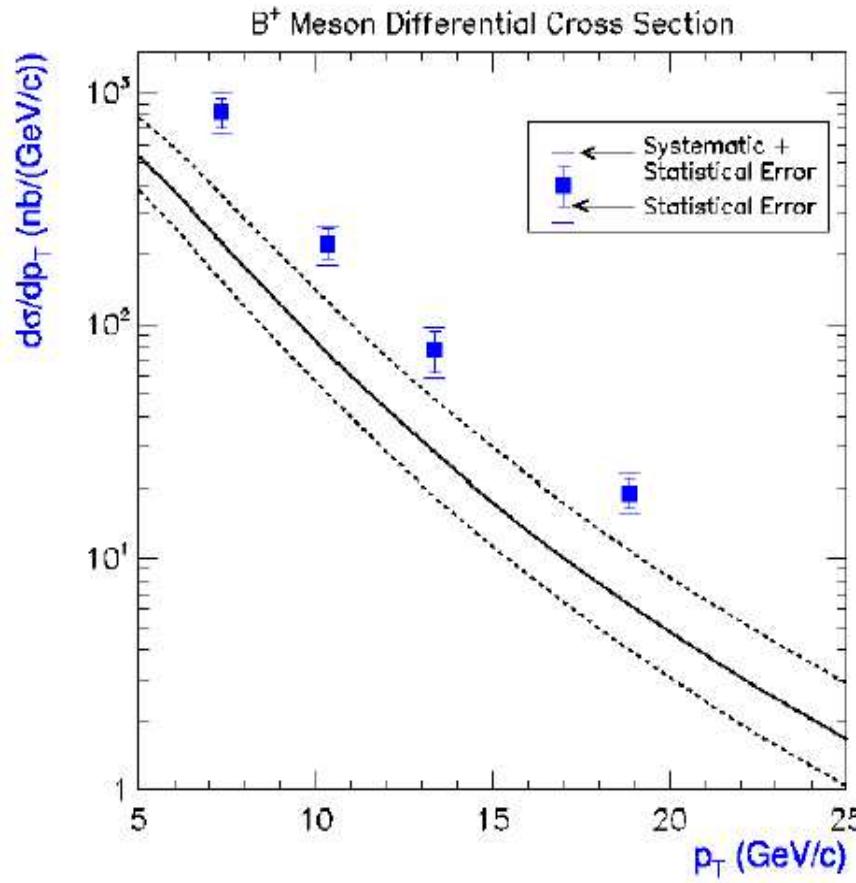
Systematic uncertainties

Source of uncertainty	Value
Uncertainties on b -fraction	
Resolution function shape (including tails)	1 – 8% (p_T dependent)
MC production spectrum	2 – 7% (p_T dependent)
MC $H_b \rightarrow J/\psi X$ decay spectrum	0.5 – 4% (p_T dependent)
MC b -hadron lifetime	1 – 4% (p_T dependent)
Background fit model	< 3% (p_T dependent)
Uncertainties on cross-section	
<u>Acceptance</u> ($H_b \rightarrow J/\psi X$)	<u>9 – 16%</u> (p_T dependent)
Inclusive J/ψ cross-section (including acceptance)	6 – 15% (p_T dependent)
Fully correlated (from inclusive)	±6.7%
Branching fractions	±8.8%

The acceptance is dominated by the lower limit of 1.5 GeV/c on the μ momentum. Largest single uncertainty is from J/ψ production polarization which impacts $J/\psi \rightarrow \mu\mu$ decay kinematics.

b-Production cross-section

$\sigma(p\bar{p} \rightarrow B^+ X)$ vs ($p_T(B^+)$)

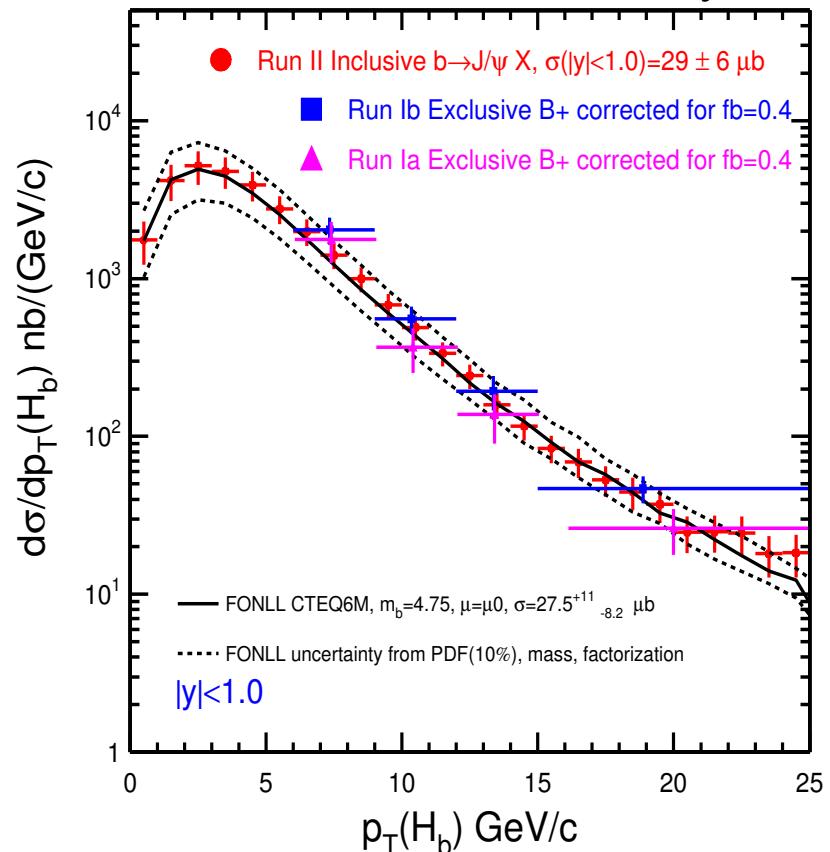


1997

Data: $\sigma = 29 \pm 6 \mu\text{b}$, FONLL: $\sigma = 27.5 \mu\text{b}$ (CTEQ6M, $m_b = 4.75$, $\mu = \mu_0$)

$\sigma(p\bar{p} \rightarrow bx)$ versus ($p_T(H_b)$)

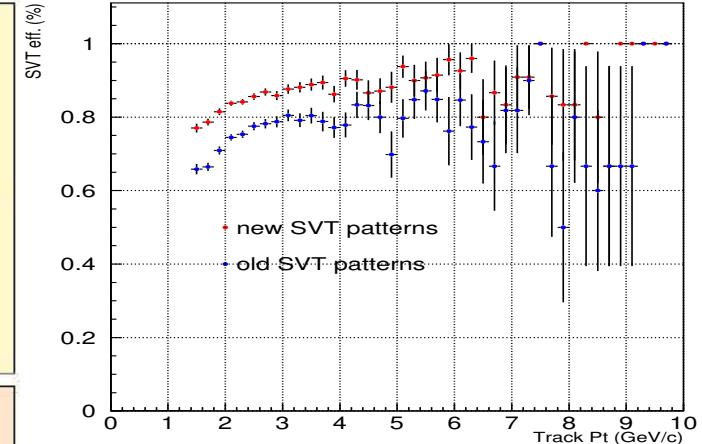
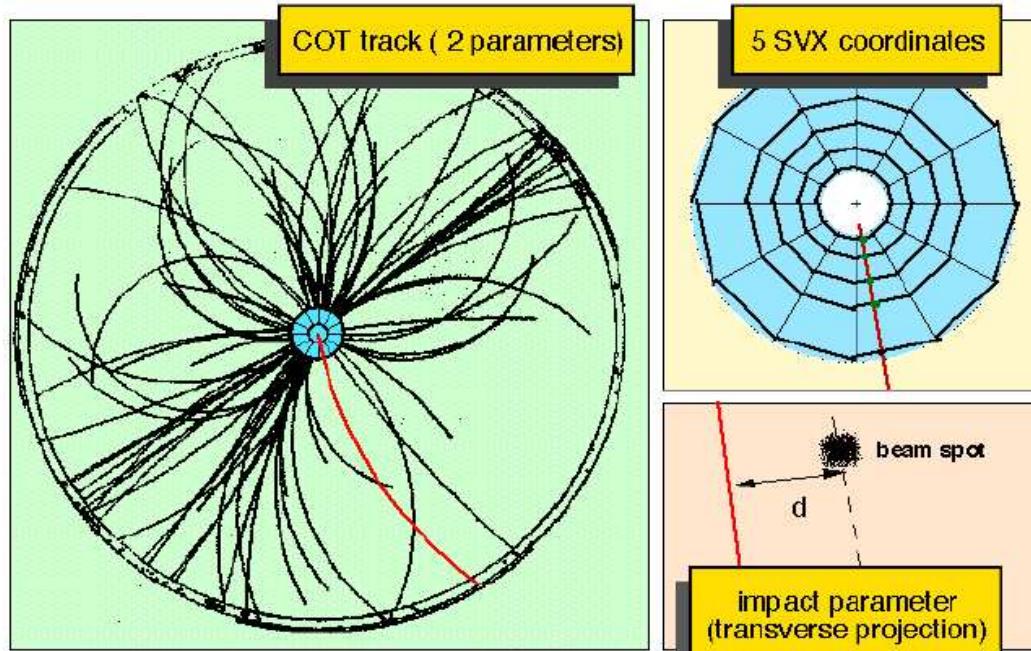
CDF Run II Preliminary



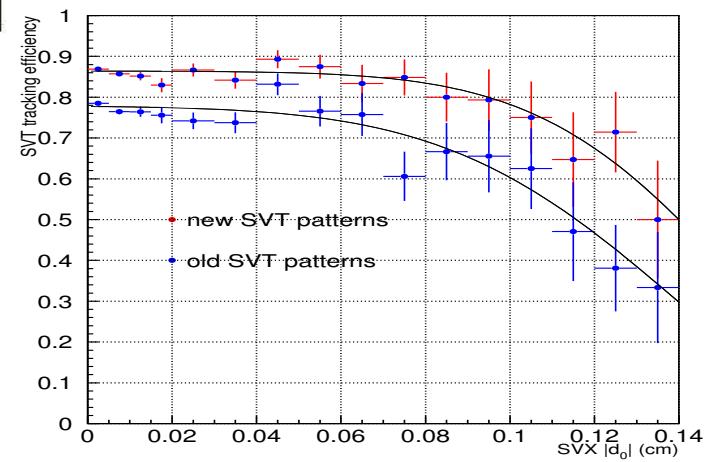
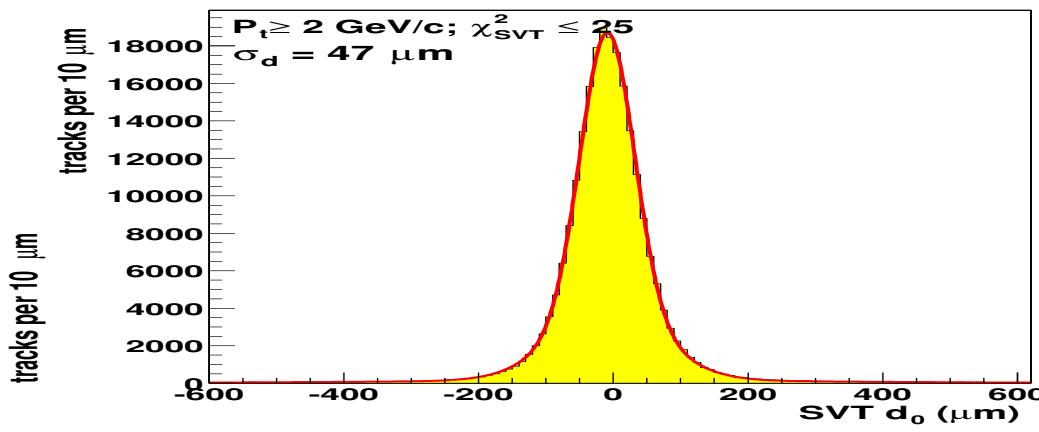
2003

CHARM MESON CROSS-SECTIONS

L2 Silicon Vertex Trigger (CDF)

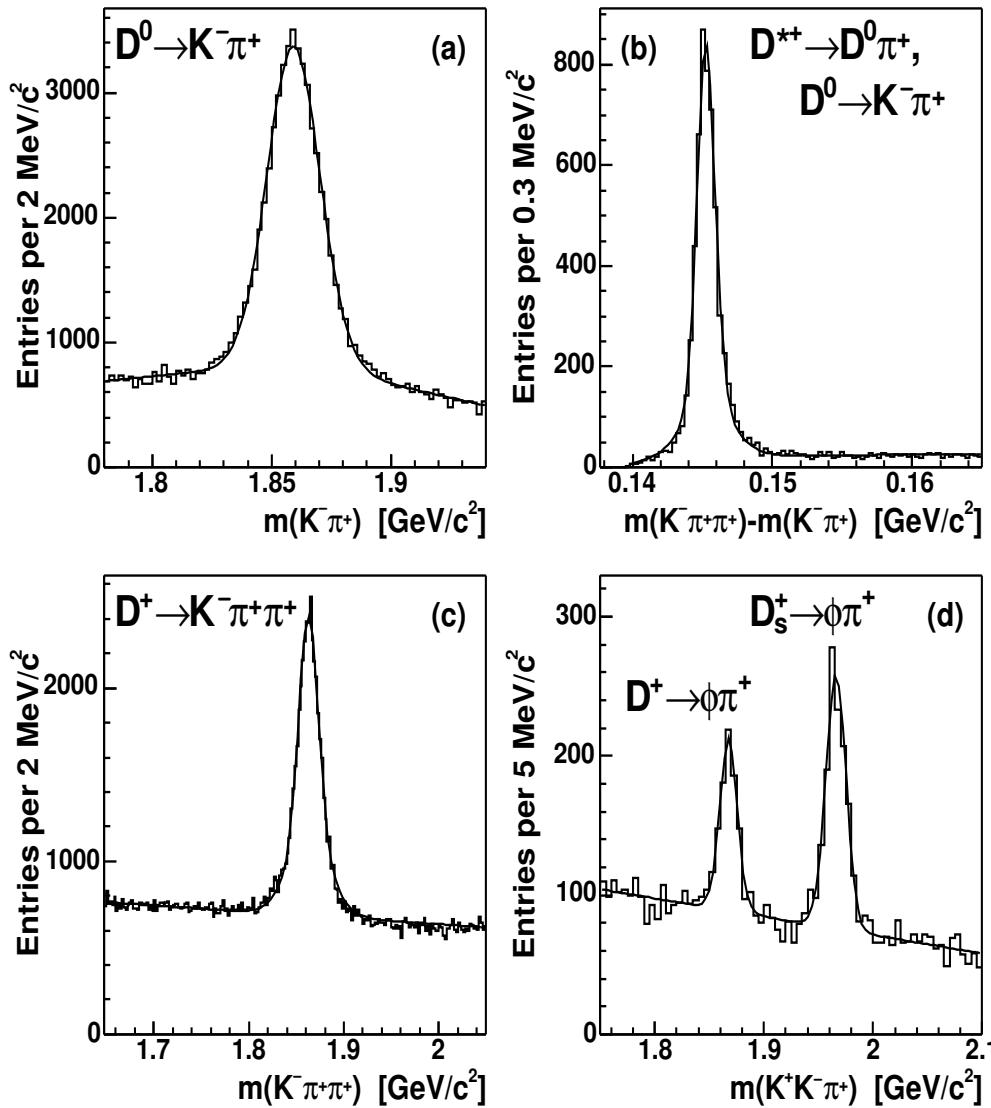


Eff. vs track p_t



SVT Eff. vs track d_0

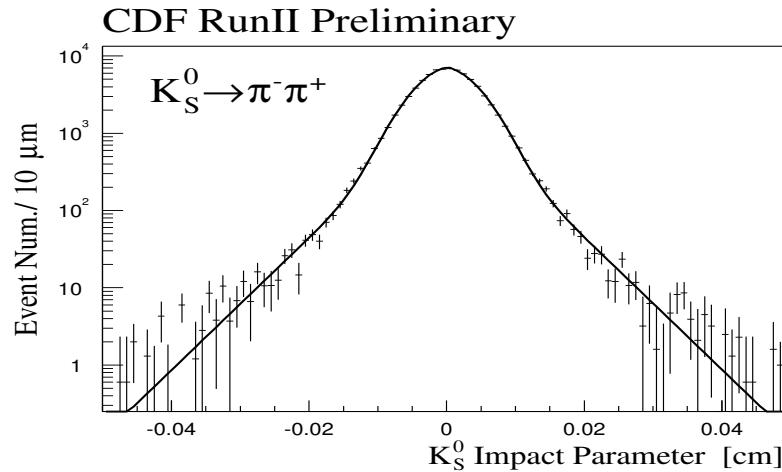
Charm Production in Run II



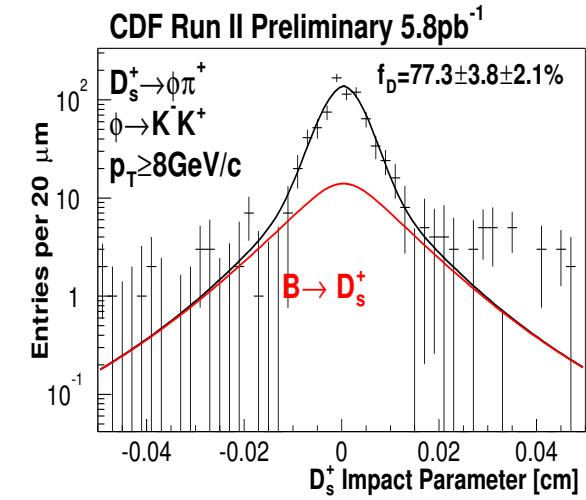
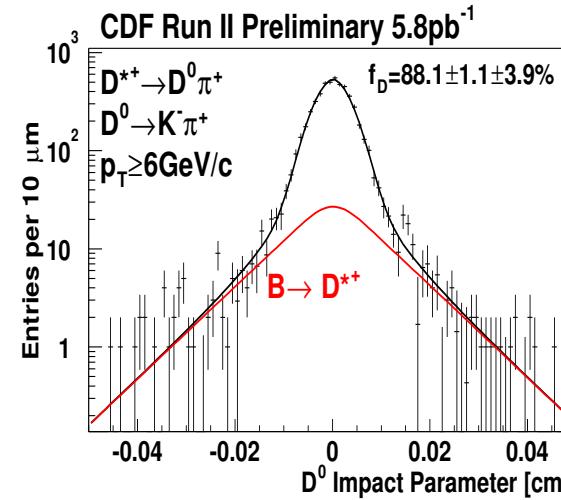
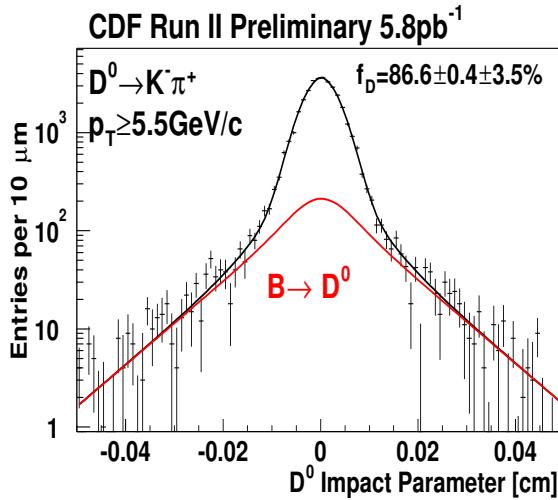
- Analysis uses 5.8pb^{-1} of early 2002 data.
- Challenges: SVT not fully efficient at the time. Efficiency is a complex function of p_T , z , $\cot(\theta)$ and time.

Direct Charm Production Run II

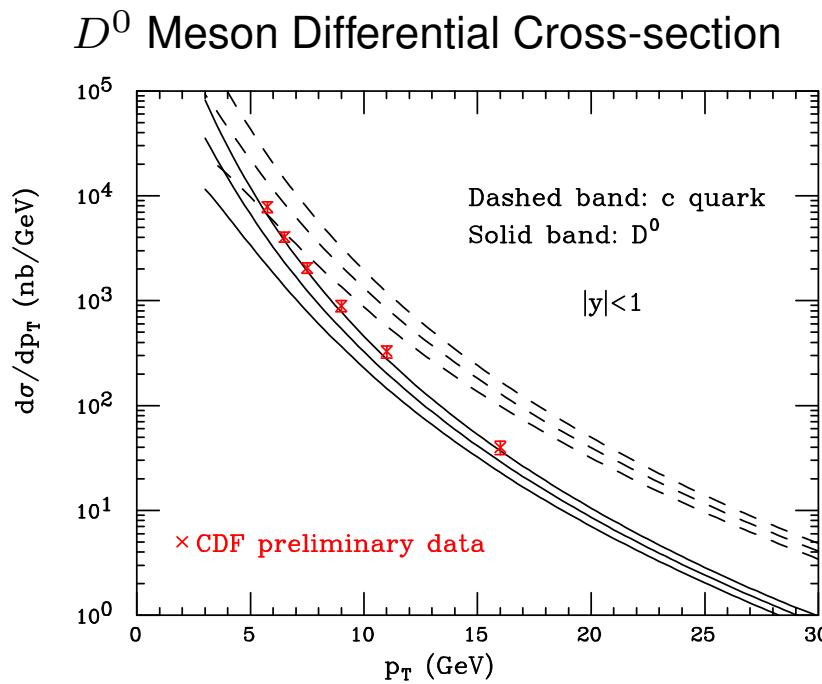
Use impact parameter of reconstructed charm mesons $F_D(d_0)$ to distinguish *directly* produced charm from $B \rightarrow DX$, $F_B(d_0)$



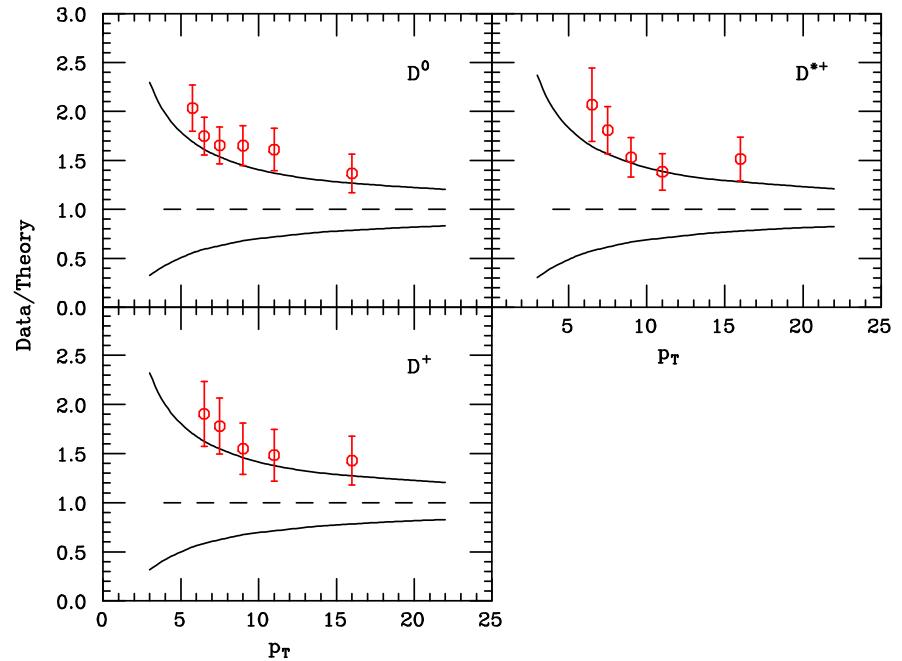
From $K_s \rightarrow \pi\pi$ data we find
 $F_D(d_0) = \text{Gaussian} + \text{exp tails}$. From $B \rightarrow DX$ MC :
 $F_B(d_0) = \text{a double exponential}$.



Charm cross-sections



D Meson Cross-sections Data/Theory



M. Cacciari, P. Nason. hep-ph/0306212.

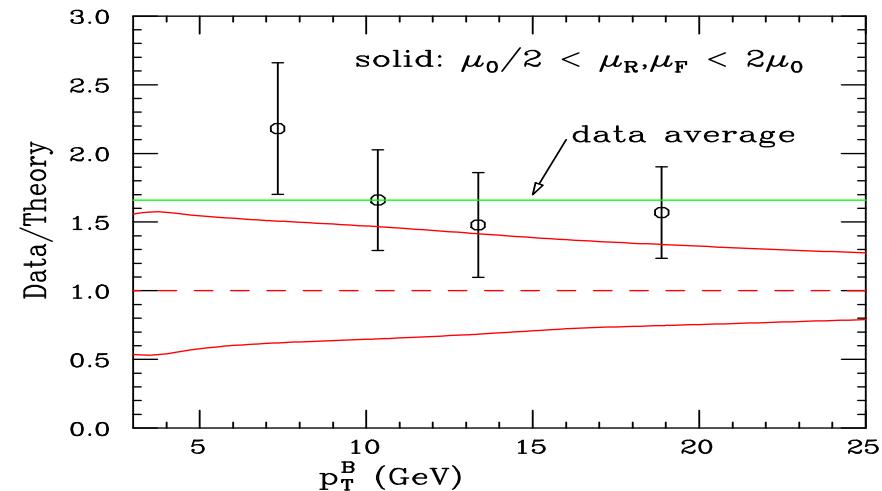
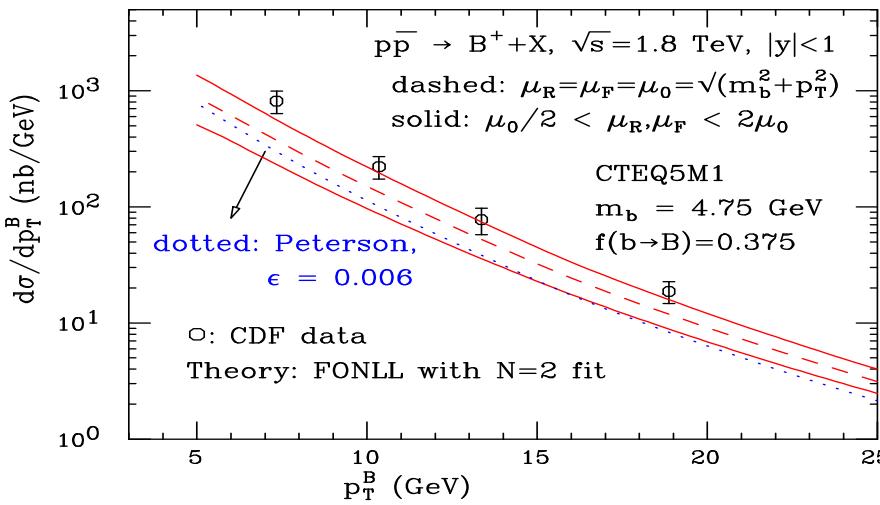
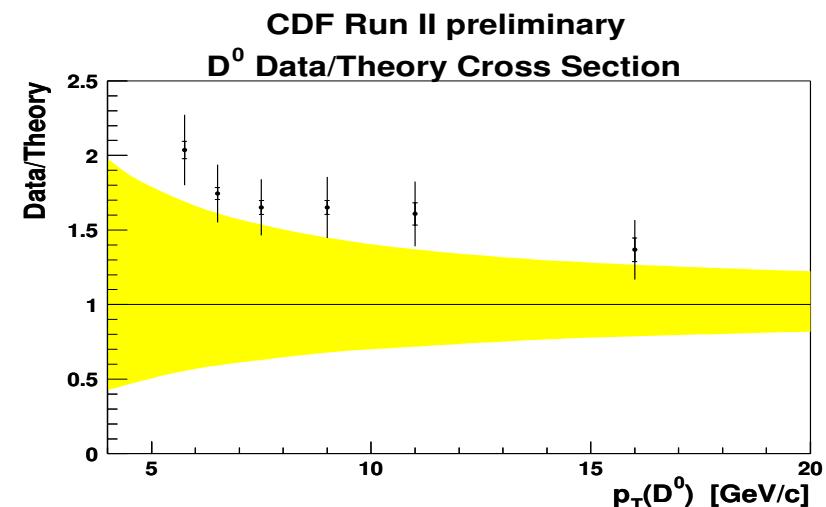
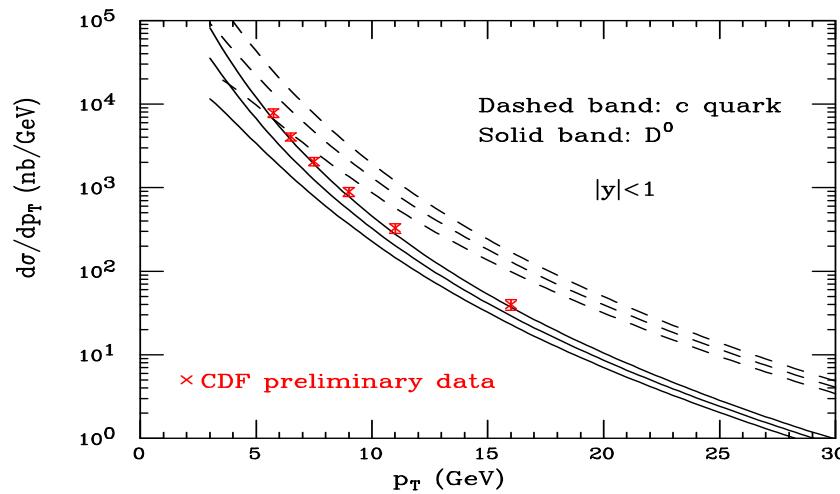
$$\sigma(p\bar{p} \rightarrow D^0 X, |y| < 1.0, p_T > 5.5 \text{ GeV/c}) = 13.3 \pm 0.2(\text{stat}) \pm 1.5(\text{syst}) \mu\text{b}$$

$$\sigma(p\bar{p} \rightarrow D^+ X, |y| < 1.0, p_T > 6.0 \text{ GeV/c}) = 4.3 \pm 0.1(\text{stat}) \pm 0.7(\text{syst}) \mu\text{b}$$

$$\sigma(p\bar{p} \rightarrow D^{*+} X, |y| < 1.0, p_T > 6.0 \text{ GeV/c}) = 5.2 \pm 0.1(\text{stat}) \pm 0.8(\text{syst}) \mu\text{b}$$

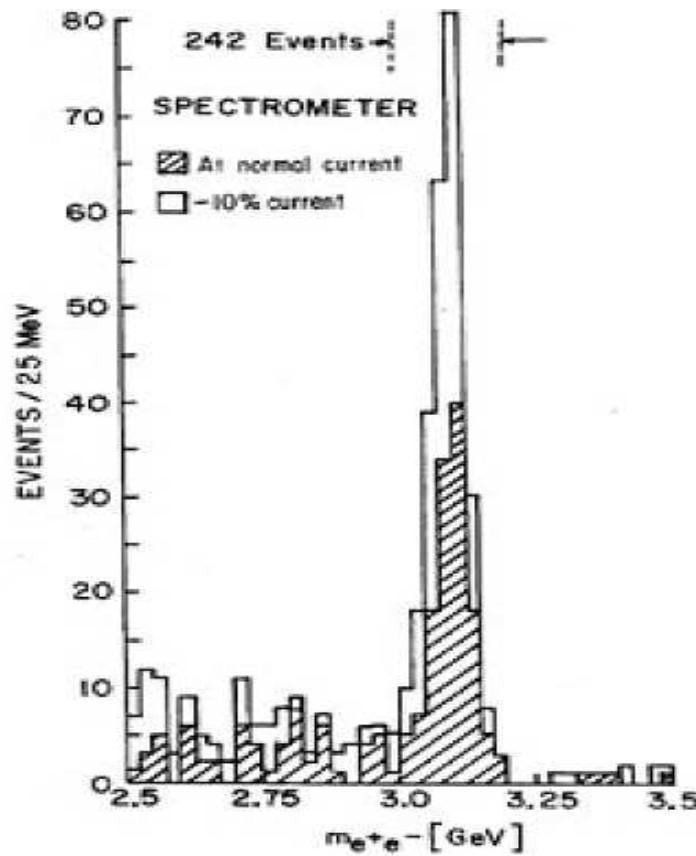
$$\sigma(p\bar{p} \rightarrow D_s X, |y| < 1.0, p_T > 8.0 \text{ GeV/c}) = 0.75 \pm 0.05(\text{stat}) \pm 0.22(\text{syst}) \mu\text{b}$$

Charm .vs. Beauty (FONLL)



Charm and Beauty meson crosssection predictions are consistent

QUARKONIA PRODUCTION

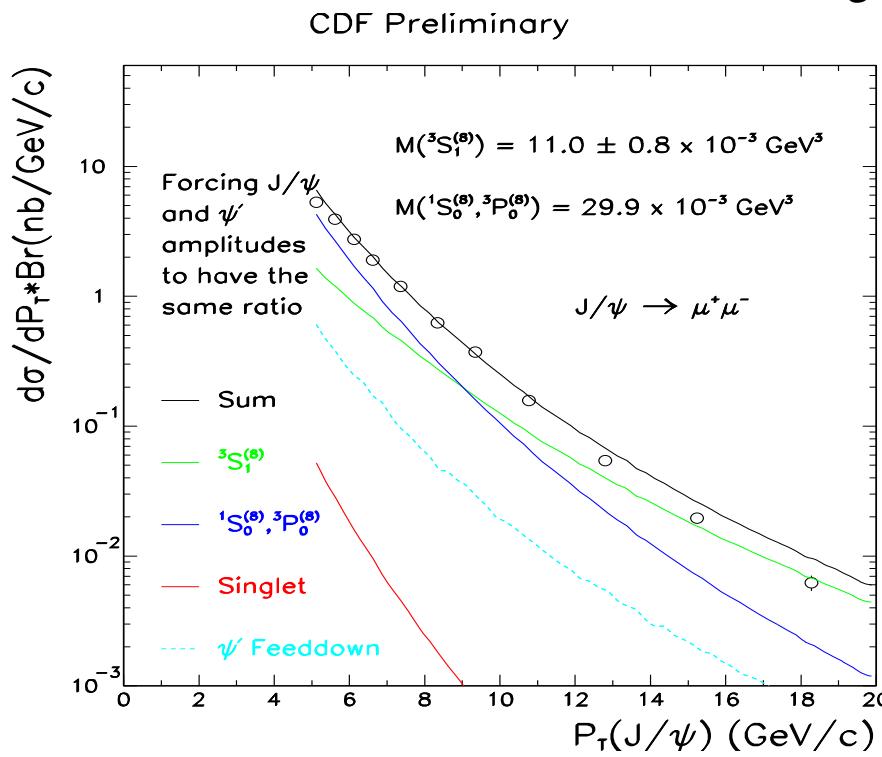


Quarkonia = discovery. J/ψ signal at Brookhaven in 1974

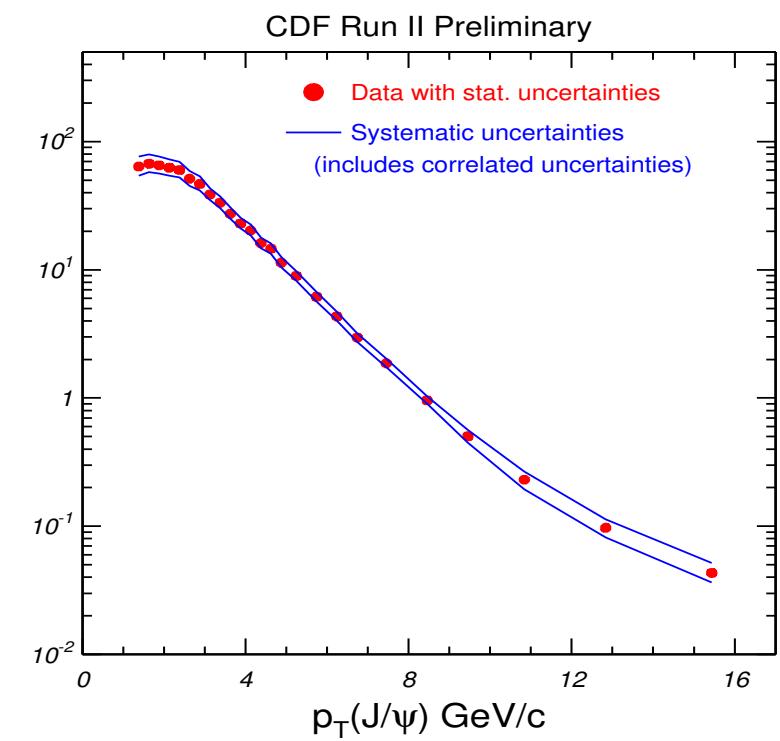
Prompt Quarkonia Production

Quarkonia bound states are *non-relativistic*. NRQCD LO perturbative expansion is $\mathcal{O}(\alpha_s^3 v^0)$ as in the color singlet model (CSM) + higher order $\mathcal{O}(\alpha_s^3 v^4)$.

Fragmentation processes \propto color octet matrix element dominate. CO matrix elements extracted from fits to data - agree well with Run I data at high p_T .



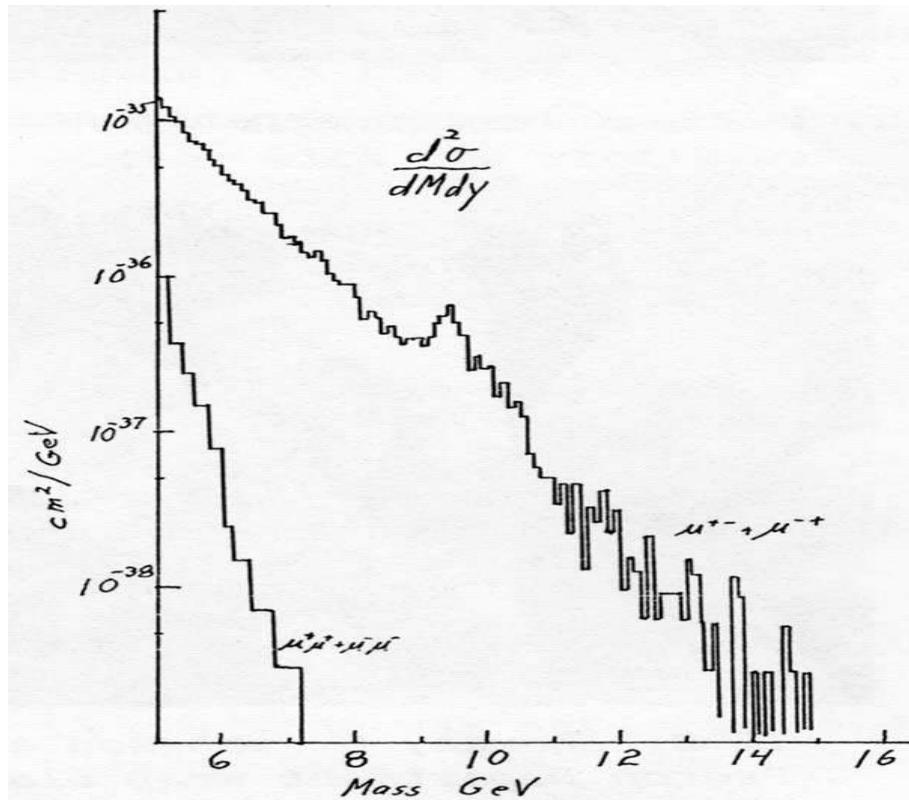
Prompt J/ψ production (Run I)



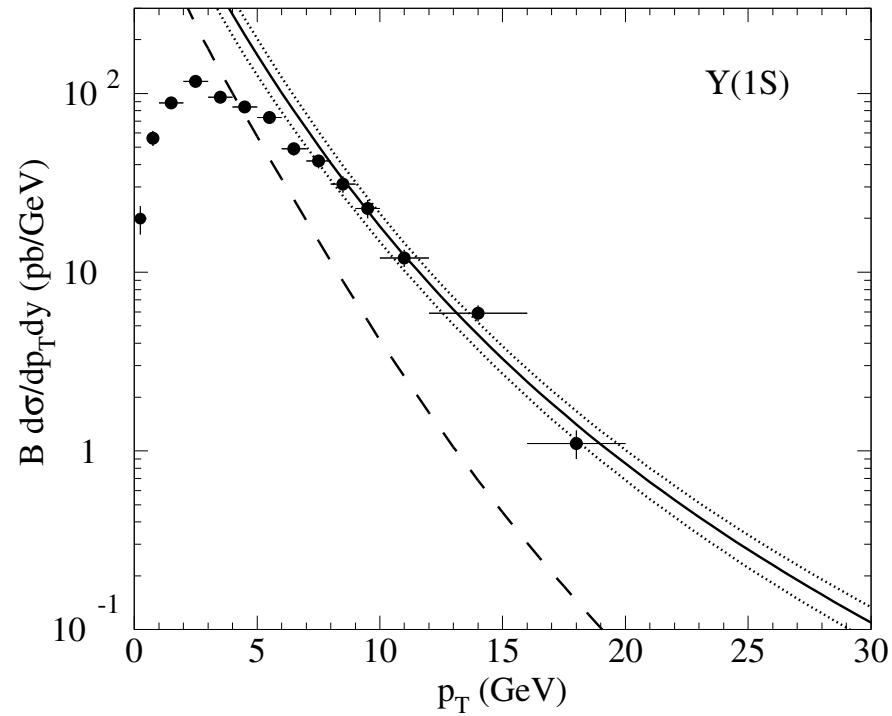
Prompt J/ψ production (Run II)

Back to Υ s!

At lower p_T NRQCD non-fragmentation diagrams from other octet matrix elements are important, soft gluon effects cause rates to diverge.



Υ discovery (1977)



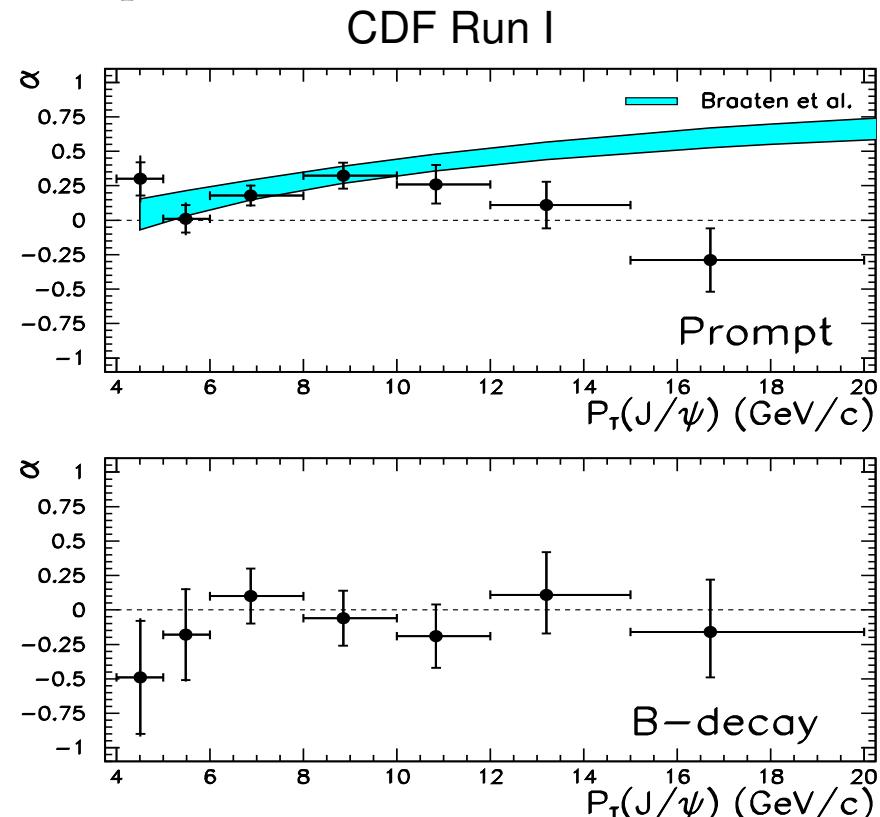
$\Upsilon(1S)$ production (Run I)

No new theoretical predictions for low p_T quarkonium at $p\bar{p}$ yet. BUT:
resummation of color octet matrix elements possible by summer 2004.

Charmonium Polarization Mystery

BUT Inclusion of color octet in NRQCD leads to a prediction of *increasing transverse polarization* of charmonium at high p_t .

Method: Fit the production angle, $\cos \theta^*$, distribution to MC distribution which is a mixture of transverse and longitudinal polarizations. Use lifetime fit method to separate prompt and $b \rightarrow J/\psi X$

$$dN/d\cos \theta^* \propto (1 + \alpha \cos^2 \theta^*)$$


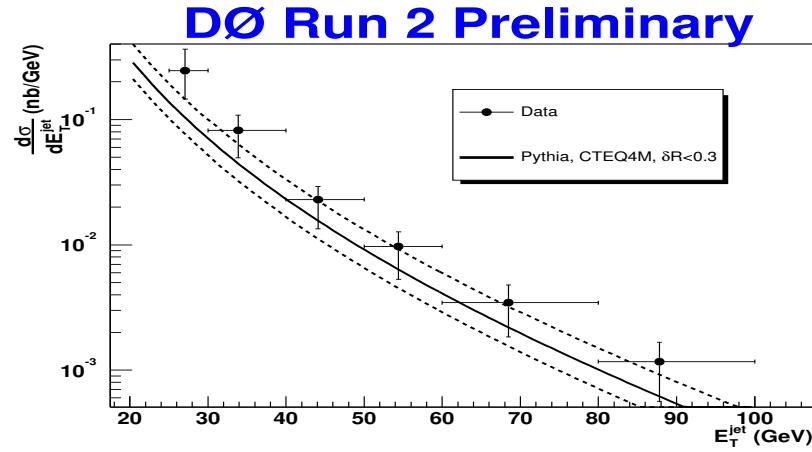
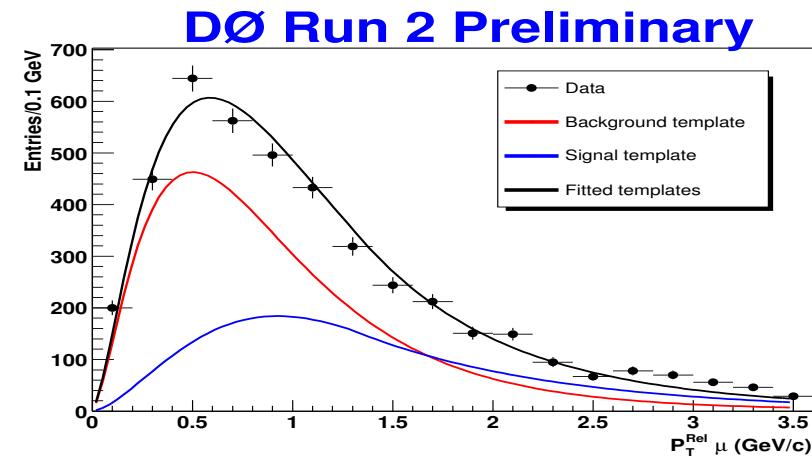
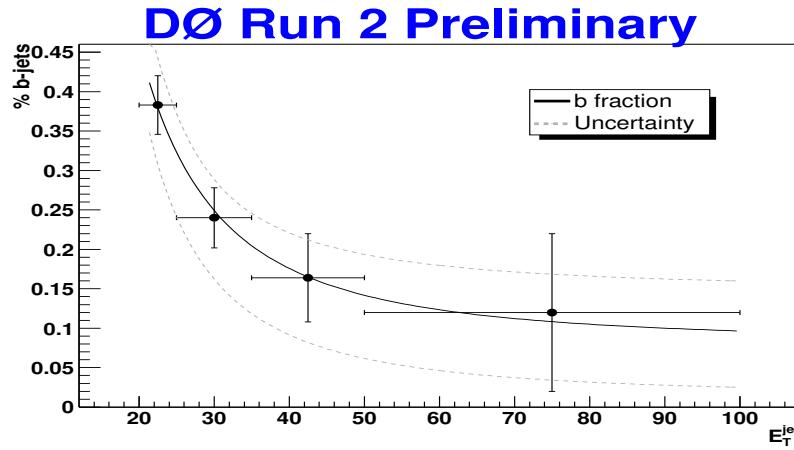
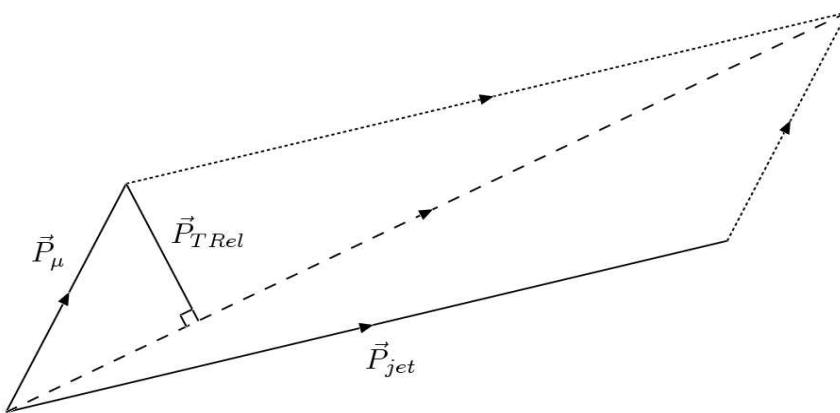
Run II :Need more precise measurements

N.B. Accurate measurements needed to reduce systematic uncertainty on detector acceptance

OTHER INTERESTING PRODUCTION TIDBITS

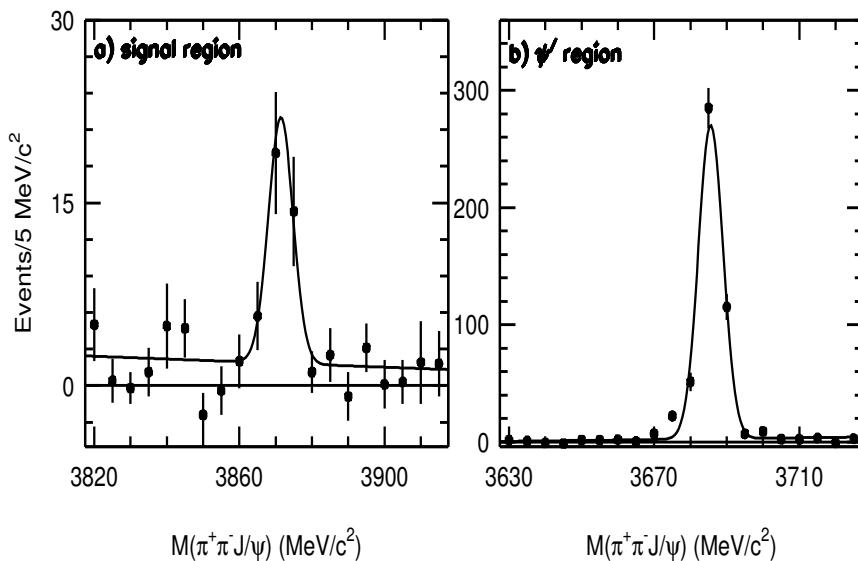
High p_T b -Jet Production

- b -jets include much of the quark fragmentation remnants \Rightarrow jet cross-sections have small dependence on fragmentation.

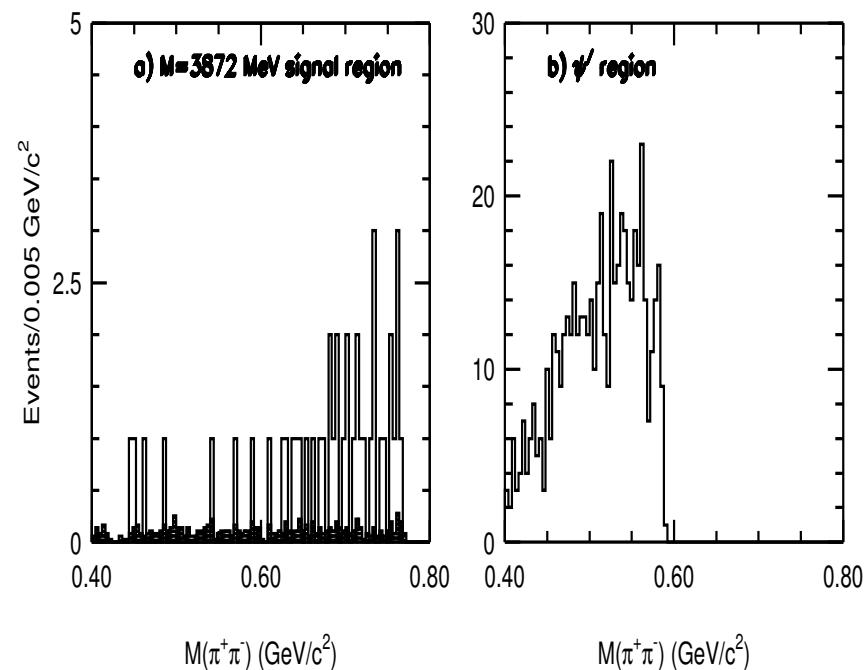


Belle observes $X(3870) \rightarrow J/\psi\pi\pi$

- At LP 2003, the Belle collaboration announced the observation of a new state decaying into $J/\psi\pi\pi$ from analysis of B decays.
- Belle signal favors large $\pi\pi$ mass

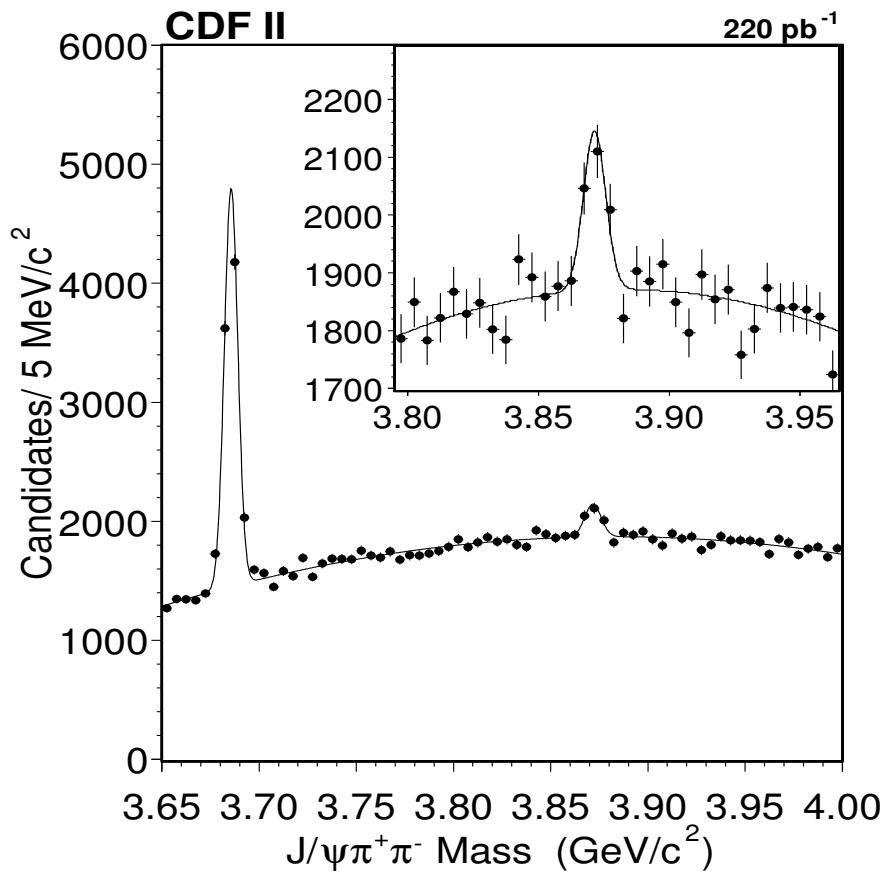


$$M = 3872.0 \pm 0.6 \pm 0.5 \text{ MeV}$$



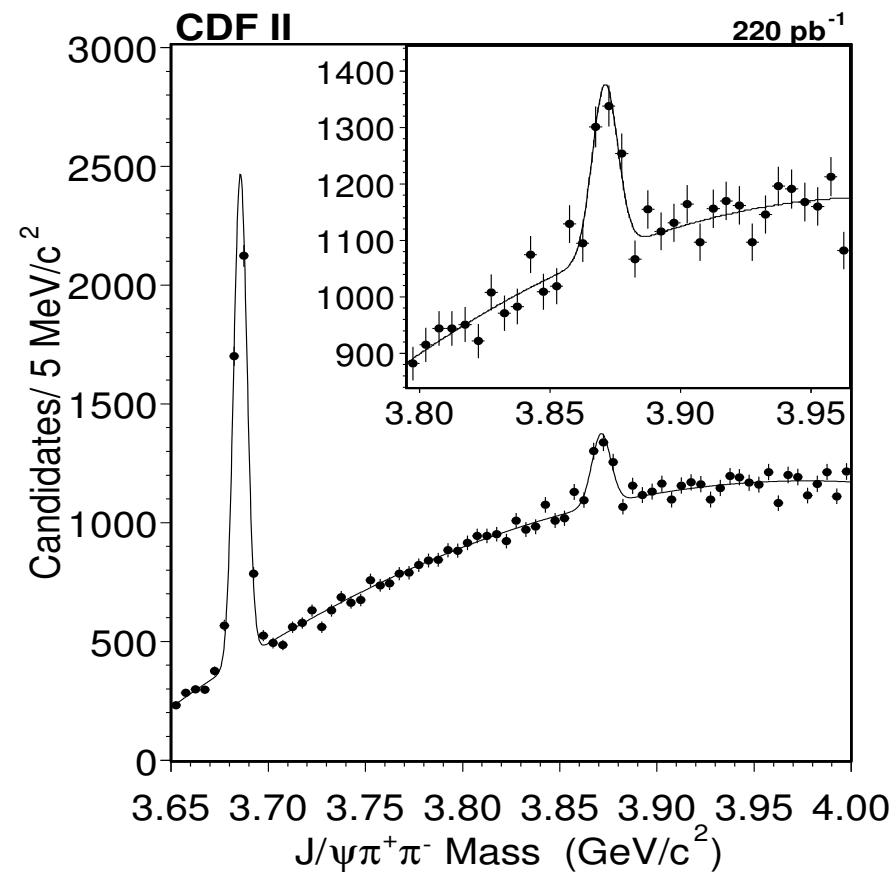
$X(3870) \rightarrow J/\psi\pi\pi$ observed in $p\bar{p}$

CDF Run II : all candidates



$$M = 3871.3 \pm 0.7 \pm 0.4 \text{ MeV}$$

CDF Run II : $m(\pi\pi) > 500 \text{ MeV}$



$$X \text{ yield: } 730 \pm 90 \text{ cand. (11.6}\sigma)$$

Submitted to PRL TODAY: hep-ex/0312021

What is it?

PDG Quark Model:

$N^{2S+1}L_J$	J^{PC}	$u\bar{d}, u\bar{s}, d\bar{d}$ $I = 1$	$u\bar{u}, \bar{d}\bar{d}, \bar{s}\bar{s}$ $I = 0$	$c\bar{c}$ $I = 0$	$b\bar{b}$ $I = 0$	$s\bar{u}, \bar{s}\bar{d}$ $I = 1/2$	$c\bar{u}, \bar{c}\bar{d}$ $I = 1/2$	$c\bar{s}$ $I = 0$	$b\bar{u}, \bar{b}\bar{d}$ $I = 1/2$	$b\bar{s}$ $I = 0$	$b\bar{c}$ $I = 0$
1^1S_0	0^{-+}	π	η, η'	$\eta_c(1S)$	$\eta_b(1S)$	K	D	D_s	B	B_s	B_c
1^3S_1	1^{--}	ρ	ω, ϕ	$J/\psi(1S)$	$\Upsilon(1S)$	$K^*(892)$	$D^*(2010)$	D_s^*	B^*	B_s^*	
1^1P_1	1^{+-}	$a_1(1235)$	$h_1(1170), h_1(1380)$	$h_c(1P)$		K_{1B}^\dagger	$D_1(2420)$	$D_{s1}(2536)$			
1^3P_0	0^{++}	$a_0(1450)^*$	$f_0(1370)^*, f_0(1710)^*$	$\chi_{c0}(1P)$	$\chi_{b0}(1P)$	$K_0^*(1430)$					
1^3P_1	1^{++}	$a_1(1450)$	$f_1(1385), f_1(1420)$	$\chi_{c1}(1P)$	$\chi_{b1}(1P)$	K_{1A}^\dagger					
1^3P_2	2^{++}	$a_2(1700)$	$f_2(1420), f'_2(1525)$	$\chi_{c2}(1P)$	$\chi_{b2}(1P)$	$K_2^*(1430)$	$D_2^*(2460)$				
1^1D_2	2^{-+}	$\pi_2(1670)$	$\eta_2(1645), \eta_2(1870)$			$K_2(1770)$					
1^3D_1	1^{--}	$\rho(1700)$	$\omega(1650)$	$\psi(3770)$		$K^*(1680)^\ddagger$					
1^3D_2	2^{--}				??	$K_2(1820)$					
1^3D_3	3^{--}	$\rho_3(1690)$	$\omega_3(1670), \phi_3(1850)$			$K_3^*(1780)$					
1^3F_4	4^{++}	$a_4(2040)$	$f_4(2050), f_4(2220)$			$K_4(2045)$					
2^1S_0	(J/ψ)	$\pi^+\pi^-$	$\eta(1295), \eta(1440)$	$\eta_c(2S)$		$K(1460)$					
2^3S_1	1^{--}	$\rho(1450)$	$\omega(1420), \phi(1680)$	$\psi(2S)$	$\Upsilon(2S)$	$K^*(1410)^\ddagger$					
2^3P_2	2^{++}	$a_2(1700)$	$f_2(1950), f_2(2010)$		$\chi_{b2}(2P)$	$K_2^*(1980)$					
3^1S_0	0^{-+}	$\pi(1800)$	$\eta(1760)$			$K(1830)$					

BUT: 3D_2 expected around $3810 \text{ MeV}/c^2$

Is this a DD^* molecule? Can CDF/D0 determine production mechanism? If mostly prompt, looks like a quarkonium rate. Is the $\pi\pi$ a ρ ?

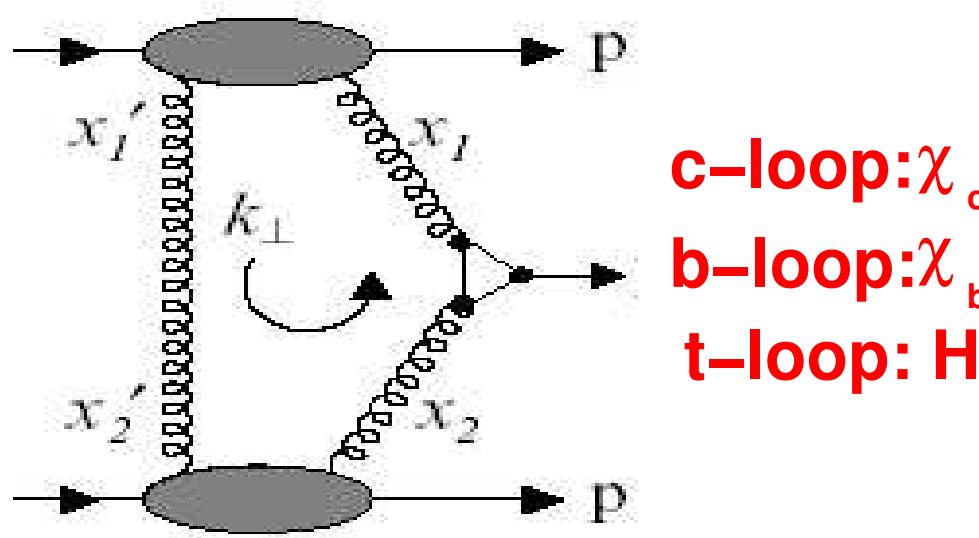
Diffractive production of χ_c

- At LHC SM Higgs boson could be produced by exclusive production with NOTHING else in the interaction ($\sigma \sim 40 \text{ fb} ?$):

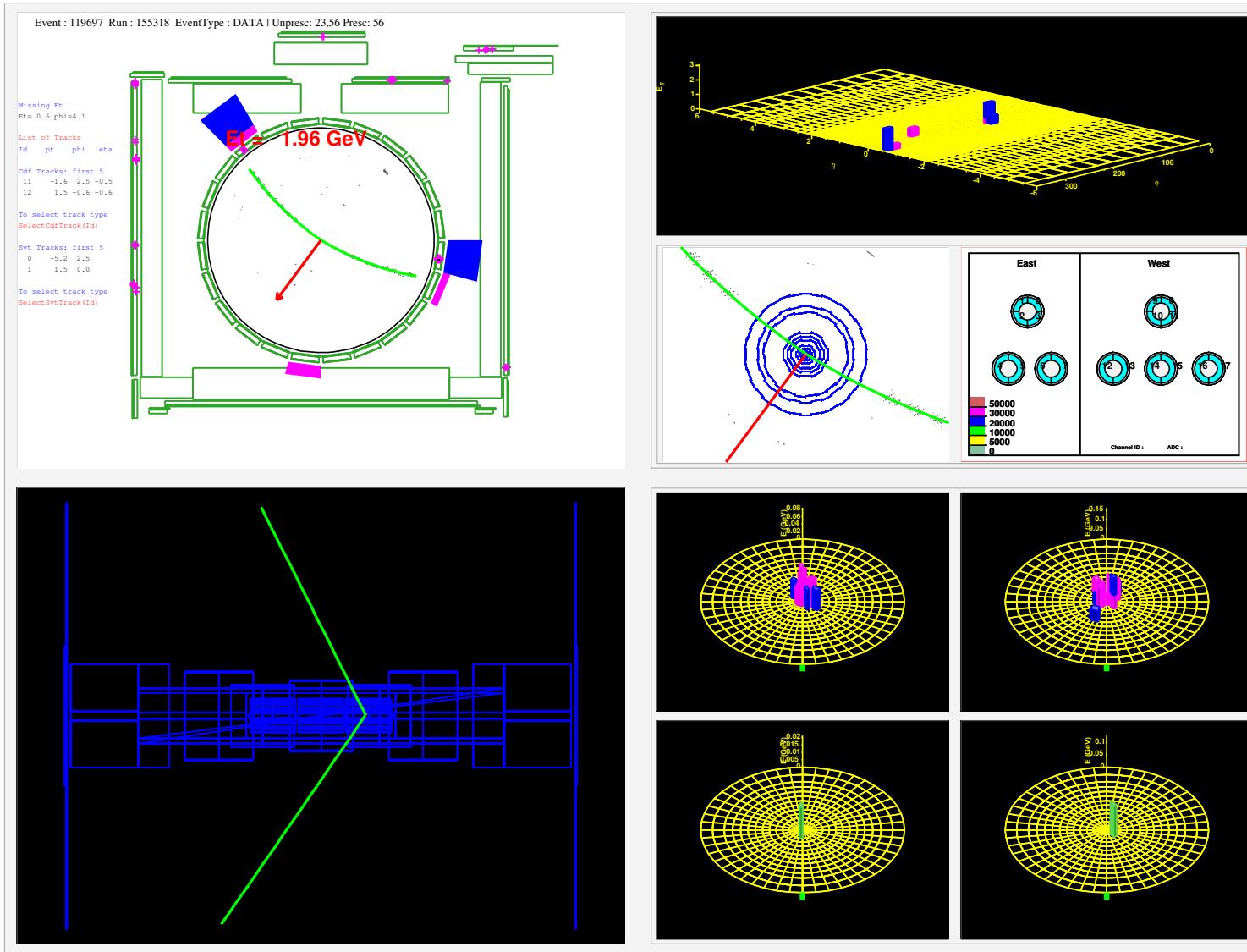
$$p + p \rightarrow p + H + p$$

- To test prediction, search for a similar process at the Tevatron:

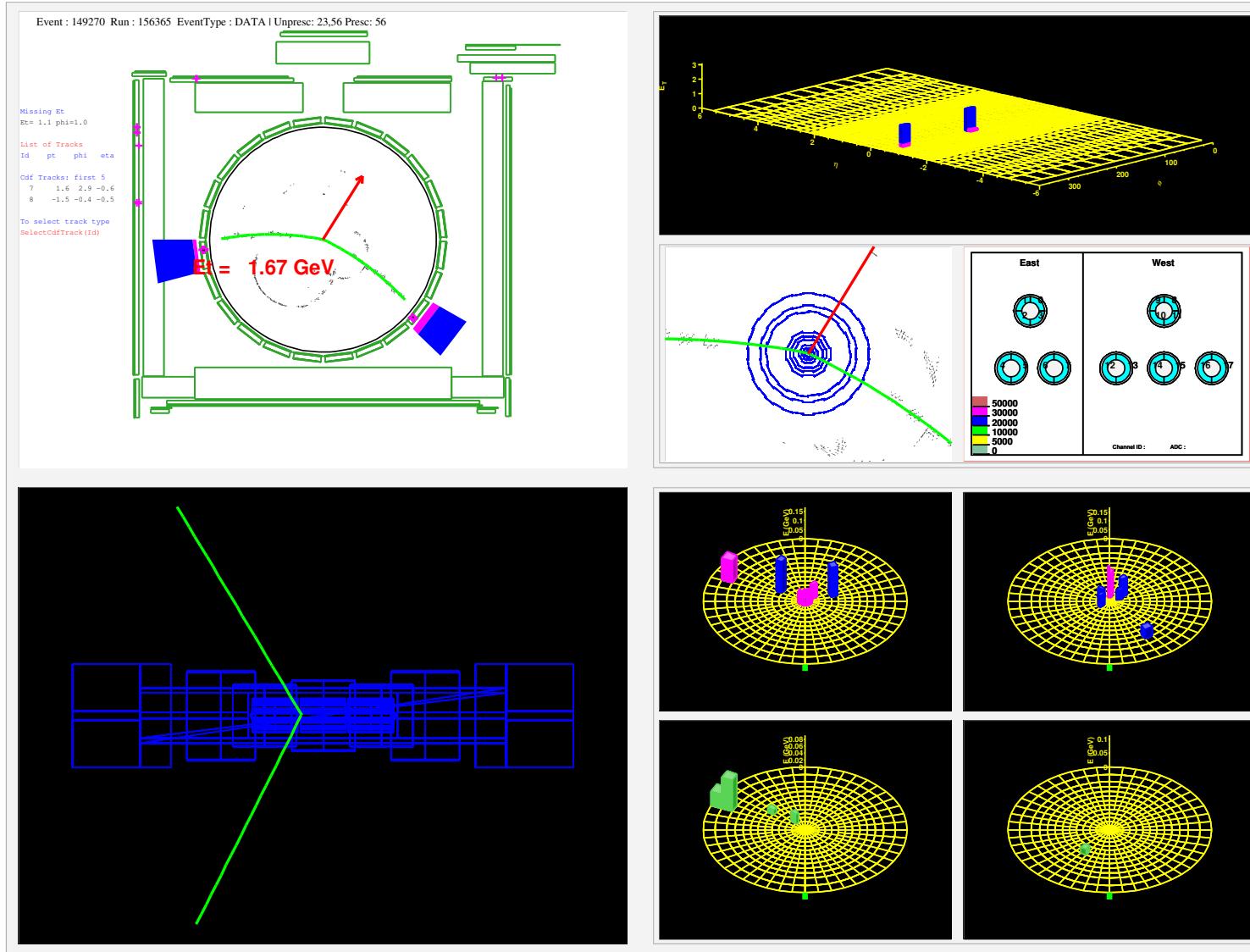
$$p + \bar{p} \rightarrow p + \chi_c^0 + \bar{p} \rightarrow p + J/\psi\gamma + \bar{p}$$



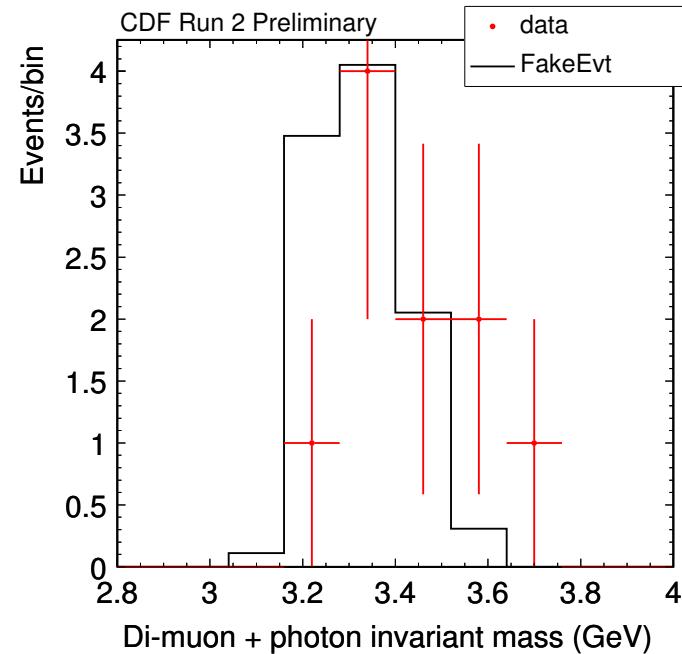
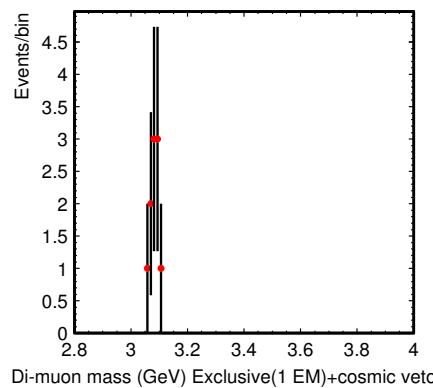
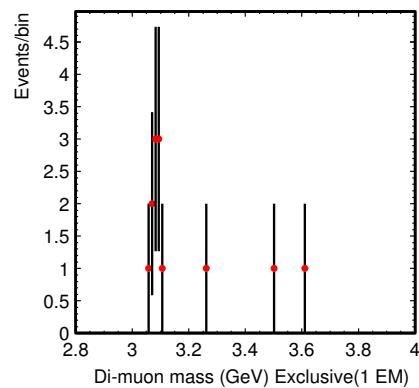
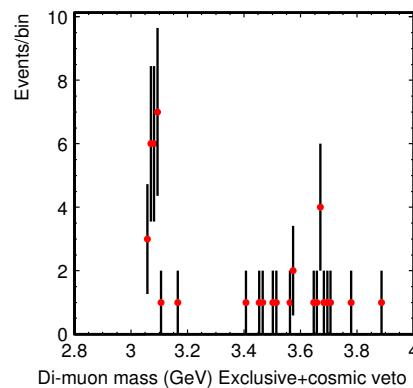
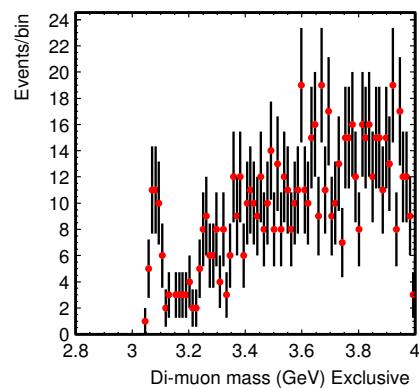
Exclusive χ_c candidate 1



Exclusive χ_c candidate 2



Analysis of exclusive events



Exclusive χ_c candidates

Need to understand backgrounds!. IF all 10 events are signal

then: $\sigma(p\bar{p} \rightarrow p\bar{p}\mu\mu\gamma, |y| < 0.6) = 49 \pm 18(stat) \pm 39(syst) \text{ pb}$

Prediction: $\sigma = \sim 200 \text{ pb}$ hep-ph/0011393

Summary

Studies of heavy quark production are precision tests of QCD at NLO.

- NEW: Run II measurements of beauty, charm, and charmonium production:
 - In 2003, new measurements of the inclusive central J/ψ cross-sections and the inclusive central b cross-sections down to $p_T = 0$ GeV/c have been carried out at CDF. *These are the first measurements down to $p_T = 0$ GeV/c at a hadron collider.*
 - Run II measurements of $D^{+,0,*}$, D_s cross-sections submitted for publication.
 - New b -jet cross-sections from D0
 - Charm spectroscopy: X(3870) confirmed at $p\bar{p}$
 - Diffractive production: exclusive $\mu\mu\gamma$ candidates observed.

-
- Lots of theory advances:
 - New PDF fits to proton structure data and better understanding of uncertainties.
 - New factorization schemes: k_T
 - Resummation of NLL for factorization schemes where quarks are massive - now valid for all p_T
 - New and improved treatments of heavy quark fragmentation

Total inclusive b -hadron cross-sections are in agreement
with theoretical predictions within uncertainties.

Charm cross-sections in reasonable agreement with theory
and consistent with beauty meson results.

Mysteries: Quarkonia production/polarization, X(3870)...
